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Ice Impacts on Flow Along the Missouri River

James L. Wuebben, Steven F. Daly, Kathleen D. White, John J. Gagnon, Jean-Claude Tatinclaux and Jon E. Zufelt

March 1995

Abstract
In recent years, drought conditions in the Missouri River basin have required more accurate control of releases at Gavins Point Dam, the furthermost downstream flow control structure on the river, to meet competing water needs for irrigation and recreation upstream and for navigation and municipal and industrial water supply downstream. In winter, ice accumulations can seriously affect flow distribution along the river. This paper summarizes a study of such ice effects. It proposes methods to determine minimum flow releases at Gavins Point Dam to meet downstream water supply without unduly depleting upstream reservoirs.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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US Army Corps
of Engineers

Cold Regions Research &
Engineering Laboratory

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March 1995

Prepared for
U.S. ARMY ENGINEER DISTRICT, OMAHA

PREFACE

This report was prepared by James L. Wuebben, Steven F. Daly, Kathleen D. White, and Jon E. Zufelt, Research Hydraulic Engineers; John J. Gagnon, Civil Engineering Technician; and Dr. Jean-Claude Tatinclaux, Chief, of the Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory.

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INTRODUCTION

This project was undertaken as part of the Missouri River Master Water Control Manual Update Project. One of the major factors prompting a review of the operation of the main stem reservoirs is the effects of extended low flow periods, such as the moderate to severe drought experienced in the Missouri River basin during the last 5 years, on water needs in the basin. This recent period of low flows has resulted in severe impacts on navigation, hydropower, water supply, and recreation. Specifically, this study has examined the impacts of winter ice formation on flow regulation and water supply requirements from Gavins Point Dam to the confluence of the Missouri and the Mississippi rivers.

During the winter months, periods of cold weather can cause ice covers or ice jams to form at numerous points along the river. Since such formations retard the flow of water, they can result in significant quantities of water accumulating (going into storage) behind them. As the water collects, upstream water levels rise until there is sufficient depth to pass all approaching water through the ice-covered reach.

During this time when water is being placed in storage, flow depths increase upstream of the ice-covered reach, and there is a corresponding decrease in water discharge and depths downstream. This flow deficit takes the form of a negative wave of reduced water flow that travels downstream, reducing water levels and perhaps impairing or preventing the operation of water intakes far downriver from the location of the ice formation. This report reviews the interrelation of water discharge and weather in forming these discharge deficit events and suggests means of regulating discharge in the river below Gavins Point Dam to minimize disruptions to the operation of municipal and industrial water intakes. Since discharge deficit events are the result of complex interactions between weather, water discharge, hydraulic geometry, and ice processes, the results are probabilistic rather than deterministic in nature. That is, the user must decide upon an acceptable level of risk prior to determining a future, ice-affected release schedule.

APPROACH

The overall plan for the project is to develop a graphical–tabular decision aid for dealing with ice-related low-flow events. The effort comprised three basic components: a statistical analysis of weather records, a review of existing ice records and ice-related low-flow events, and a synthesis of the first two components to allow an empirical estimate of ice effects based on predicted weather conditions and planned water discharges. This graphical–tabular approach allows a user to estimate required releases from Gavins Point Dam for either annual planning using long-term statistical information or a near-term response to an anticipated cold snap based on current weather, levels, and flows.

For the case of long-term planning, the user must select an acceptable level of risk. Then, based on weather statistics and long-term average discharge patterns and corresponding to the selected risk, anticipated minimum release requirements from Gavins Point Dam can be defined to ensure adequate water depths for water intakes. Using this approach, the recommended minimum releases are defined for each 2-week time period throughout the winter ice season. This release plan is based solely on long-term weather and discharge patterns and does not consider current year weather or tributary inflows.

The second approach is targeted at near-term operation. It allows the user to estimate the magnitude

of an anticipated discharge deficit event (water placed in storage) based on the severity of the winter prior to the current date, forecasted weather, and (once again) an acceptable level of risk. Based on this estimated discharge deficit and current water levels and flows throughout the system, the user could determine whether an increase in water release is required, and if so, the amount.

ANALYSIS OF ICE AND DISCHARGE DATA

To develop a predictive method for determining the required winter releases at Gavins Point Dam, it is necessary to identify ice events that are associated with decreases in flow. Two sources of information are available in this case: visual observations of ice cover presence and USGS gaging station discharge data.

MRD ice data sheets

Long-term visual ice observations are rare. Fortunately, Missouri River Division (MRD) personnel have made careful observations of ice covers on the Missouri River. These are shown graphically on the MRD ice data sheets, which span from St. Louis, Mo. (river mile 0) to Gavins Point Dam (RM 811) for the period 1963 to present. A portion of an ice data sheet is shown in Figure 1. These sheets indicate the presence or absence of an ice cover and, in some cases, the estimated percent coverage of the river by floating ice. In this study, an ice cover recorded on the sheets was considered to represent the occurrence of an ice event capable of causing water to go into storage, thereby decreasing flow.

Starting and ending dates of ice events are generally well defined. The initiation point of some ice jams is clear, but in other cases it must be estimated. However, the error is small and the ice data sheets are extremely valuable in identifying the location of initiation points. The location of the upstream edge of the ice cover is open to interpretation in many cases, but very well defined in a few instances. Progression and regression rates of several ice events can be determined from the ice data sheets.

USGS gaging station records

Normally, discharge in an uncontrolled river increases in the downstream direction, provided consumptive water use is not large in relation to river flow. Decreases in discharge in the downstream direction are often a result of water going into storage. If a significant amount of water goes into storage as a result of ice formation and jamming, discharge decreases in the downstream direction so that recorded discharge is lower at a downstream gaging station than at an upstream gaging station. Examination of stream gaging records during the winter months can be useful in estimating the occurrence and location of ice jams.

To evaluate discharge data in this manner, the Missouri River below Gavins Point Dam was broken up into nine reaches (Fig. 2), divided by USGS gaging stations (Table 1). The reaches are listed in Table 2, along with the ice jam initiation locations indicated on the MRD ice data sheets that occur within each reach. The average daily discharge from November through March was plotted for water years 1968 through 1988 for the USGS gaging stations listed in Table 1. Examples of such plots for the 1968 water year are given in Figure 3.

The most upstream reach (reach 1) extends from the USGS gage at Sioux City (RM 732.2) to the USGS gage at Yankton (RM 805.8), which is 5.2 miles downstream from Gavins Point Dam. There are no

Table 1. Station information for discharge-based reaches.

Station	*USGS gage no.*	*Location (river mile)*	*Years of record**	*Drainage area (mi²)*
Yankton	06467500	805.8	1930–current	279,500
Sioux City	06486000	732.2	1939–current	314,600
Omaha	06610000	615.9	1928–current	322,800
Nebraska City	06807000	562.6	1929–current	410,000
Rulo	06813500	498.0	1949–current	414,900
St. Joseph	06818000	448.2	1928–current	420,300
Kansas City, Missouri	06893000	366.1	1928–current	485,200
Waverly	06895500	293.5	1928–current	487,200
Booneville	06909000	196.6	1925–current	501,700
Hermann	06934500	97.6	1928–current	524,200

*Continuous daily records

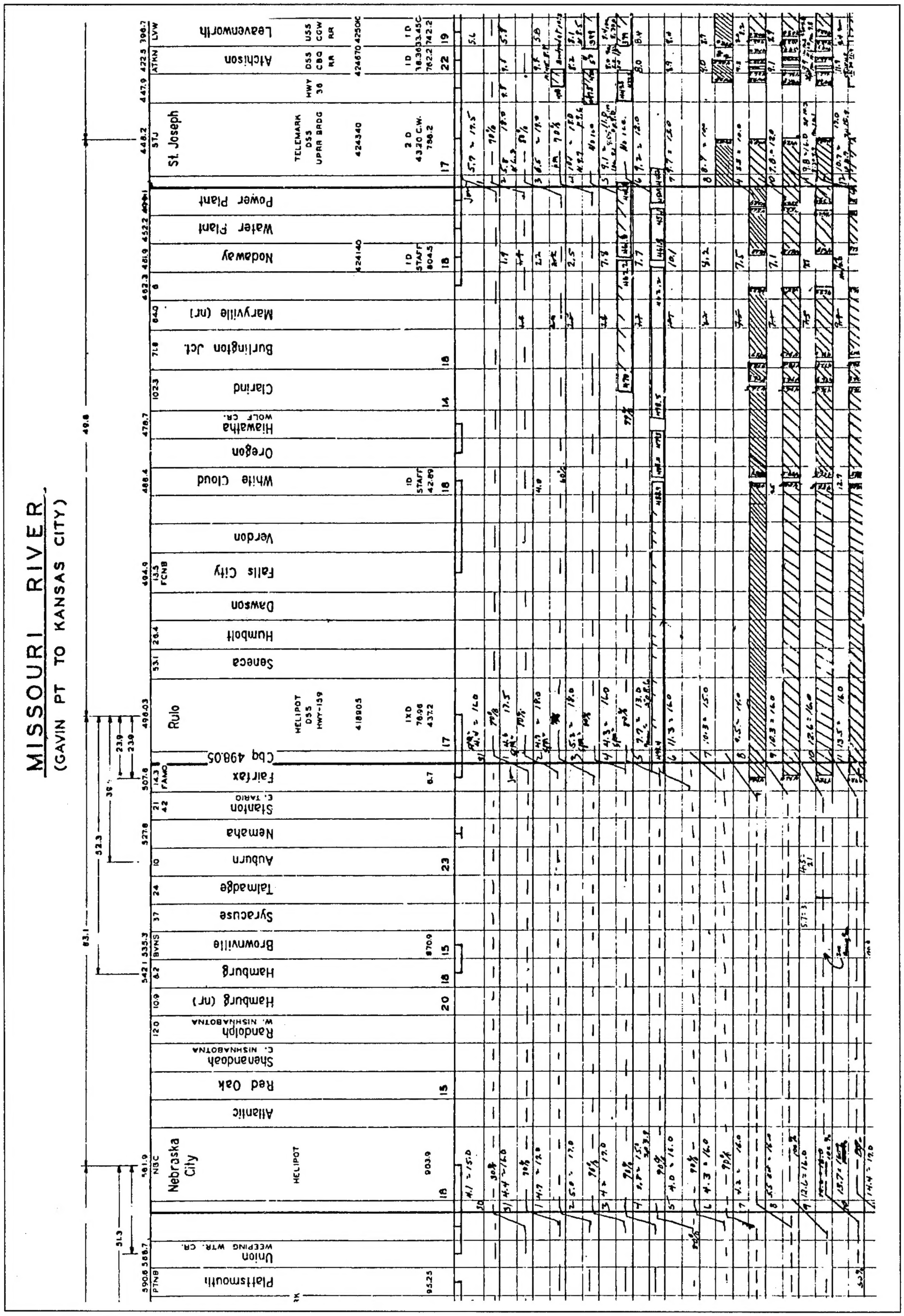


Figure 1. Portion of MRD ice data sheet for January 1968.

Table 2. Overview of discharge-based reaches.

Reach no.	*Upstream station*	*Downstream station*	*Known jam initiation points within reach**	*River mile*
1	Yankton	Sioux City	Scotland	797
2	Sioux City	Omaha	Decatur	691
			Blair	648
3	Omaha	Nebraska City	South Bend	596
4	Nebraska City	Rulo	Randolph	548
			Hamburg	542
			Brownville	535
5	Rulo	St. Joseph	Falls City	495
			White Cloud	488
			Verdun	491
			Clarind	474
			Burlington Junction	470
			Maryville	466
			St. Joseph	448
6	St. Joseph	Kansas City, Mo.	Atchison	422
			Leavenworth	396
			Diagonal Creek	395
			Agency	393
			Smithville/Platte City	392
			Kansas City, Ks.	374
			Kansas City, Mo.	370
			Bonner Springs/DeSoto	368
			Kansas City, Mo.	366
7	Kansas City	Waverly	Grand Ave	365
			Choteau Brook	362
			Lake City	339
			Sibley	336
			Napoleon	329
			Richman	312
			Waverly	293
8	Waverly	Booneville	Sumner	250
			Prairie Hill	239
			Glasgow	226
			Valley City	217
			Clifton Creek	202
9	Booneville	Hermann	Fayette	186
			Booneville West	178
			Moniteau Creek	158
			Jefferson City/ Capital City WW	144
			Bagnell Dam	130
			Chamois	117
			Rich Falls	104
			Hermann	98

*Initiation points from MRD ice data sheets
Approximate river mile of initiation points shown

major tributaries between Gavins Point Dam and the gage at Yankton. Therefore, for this analysis, changes in discharge at Gavins Point Dam are assumed to cause corresponding changes in discharge at Yankton.

The plots of discharge data were used to estimate ice jam events in the following manner: If the discharge of the station at the downstream end of the reach decreased below the discharge at the upstream station (a "dip"), an ice event was assumed to have occurred in the intervening reach beginning on that date.

Some ice jam events may have caused a decrease in discharge large enough to cause problems although still not decreasing discharge enough to cause a dip between upstream and downstream sta-

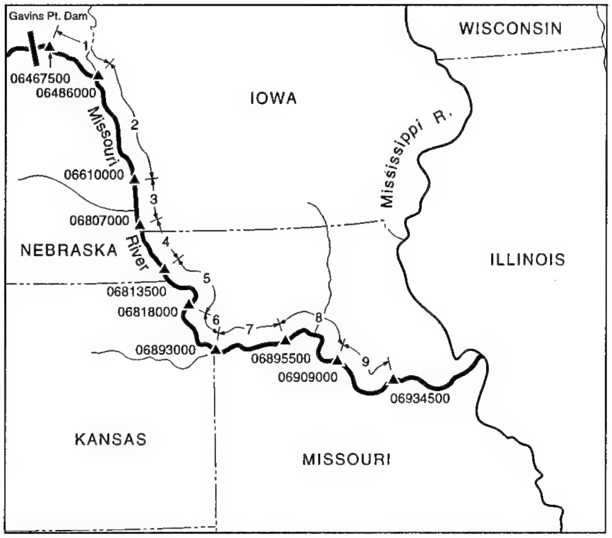


Figure 2. USGS gaging stations and reaches used in discharge analysis.

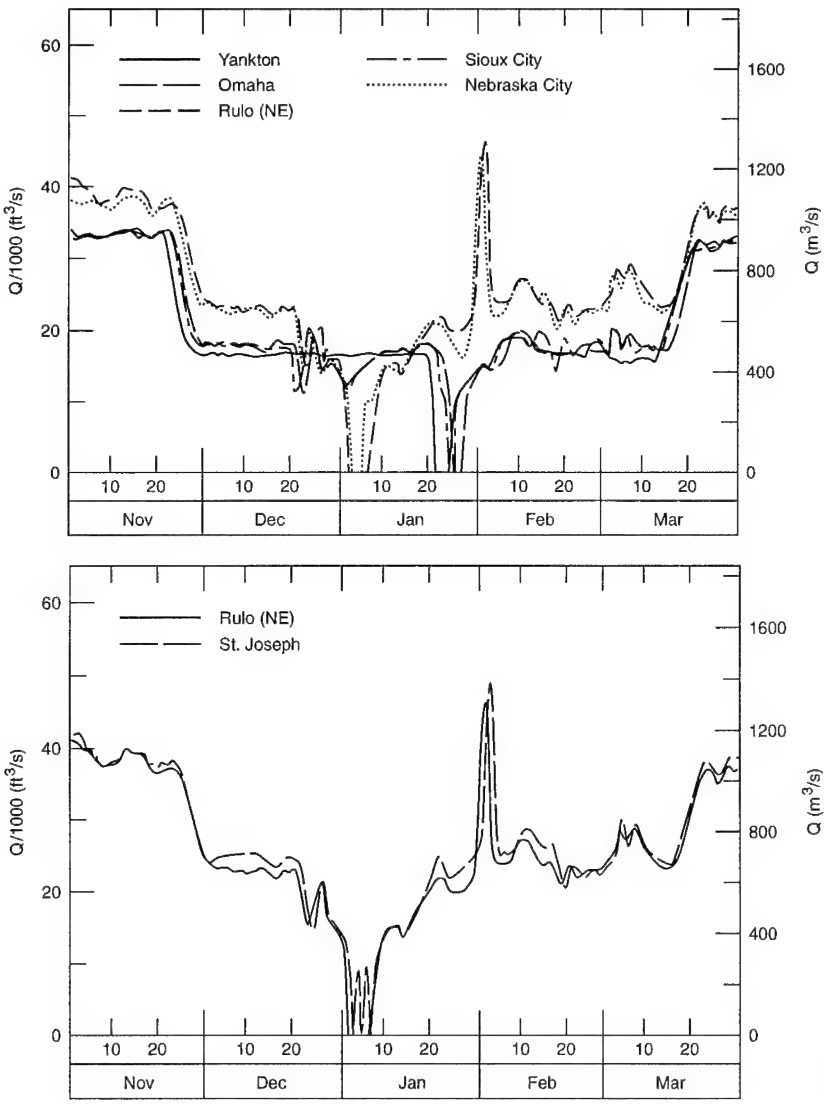


Figure 3. River discharge for winter of water year 1968.

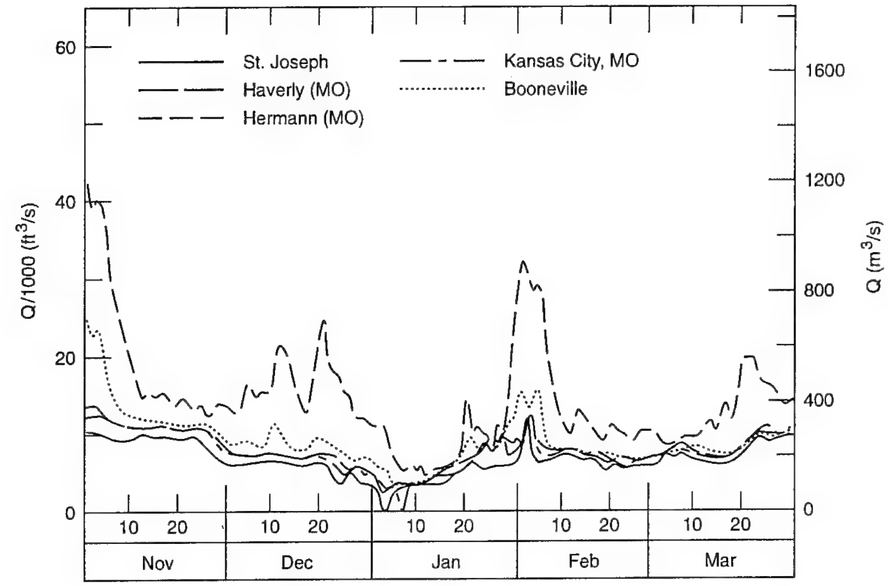


Figure 3 (cont'd). River discharge for winter of water year 1968.

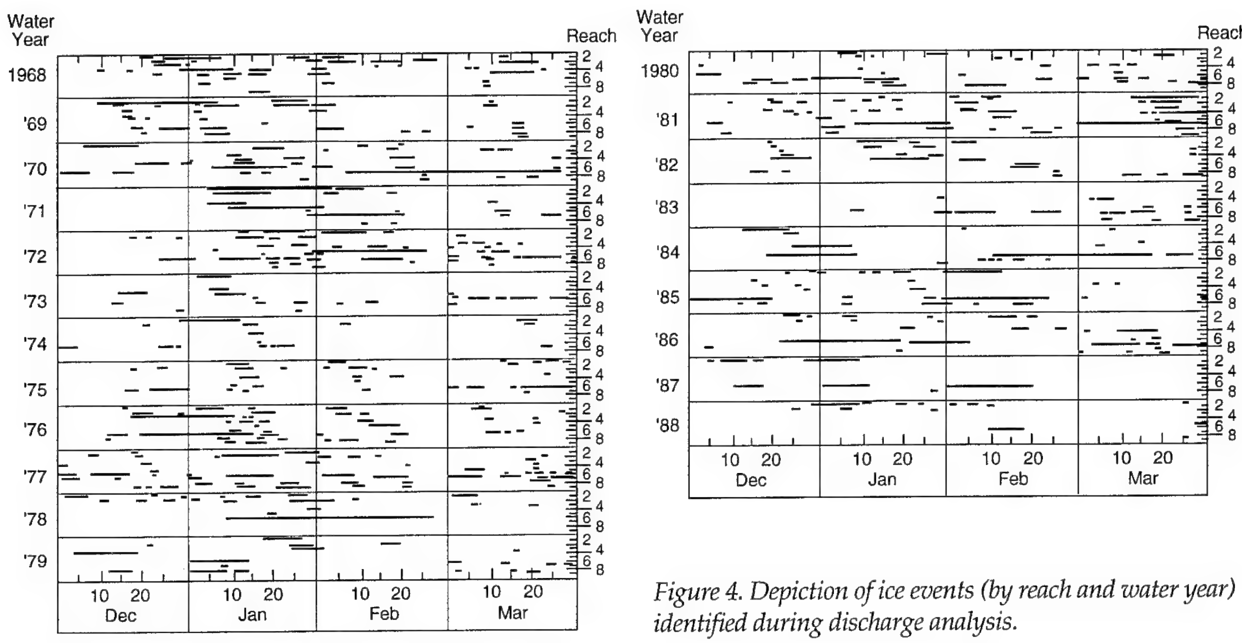


Figure 4. Depiction of ice events (by reach and water year) identified during discharge analysis.

tions. For example, in reaches with few ice jam initiation points and those with a large incremental drainage area, such as reaches 3 and 6, ice events would have to involve an extensive amount of water storage to cause a dip. As a result, this type of discharge analysis is likely to underestimate the occurrence of ice events that cause localized decreases in discharge, but is unlikely to predict an ice event when none occurs.

The duration of the periods of decreasing discharge (dips) was plotted by water year for each reach based on the discharge data (Fig. 4). These plots indicate that decreases in discharge between Yankton and Sioux City can be traced downstream generally as far as St. Joseph. In some cases, the effect of the initial dip can be traced farther (see December, water year 1969). It is difficult to distinguish the effects of these "traveling dips" from intermediate ice jams that occur simultaneously in downstream reaches or later than the initial event.

Evaluation of ice event data

The number and location of ice events estimated using the two sources of data must be evaluated for

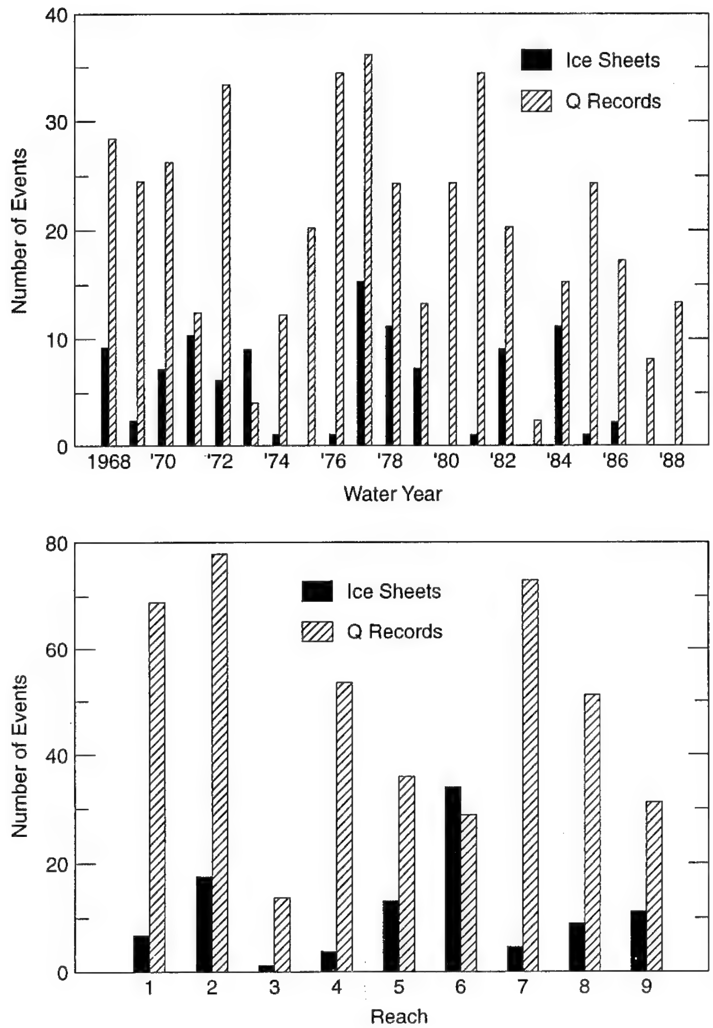


Figure 5. Ice events recorded on MRD data sheets and by discharge analysis: a) all reaches by year and b) all years by reach.

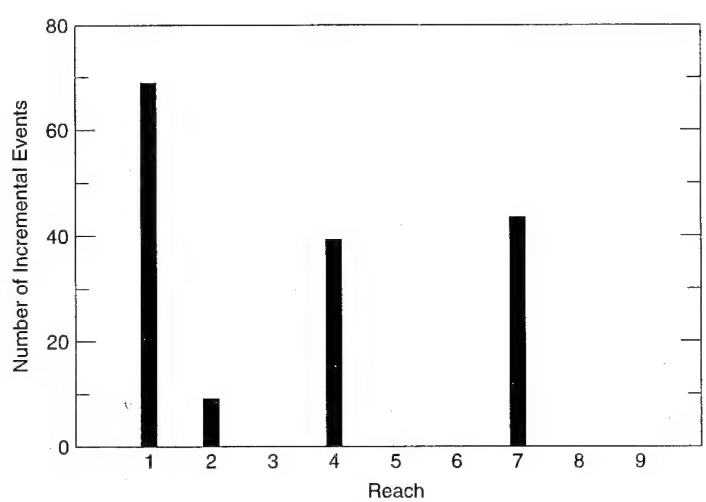


Figure 6. Incremental increase in ice event by reach.

reliability. As noted previously, the number of ice events tabulated using the USGS gaging records may be underestimated in reaches with few jam initiation points or with large incremental drainage areas. For example, reach 7 has the smallest incremental drainage area (2,000 square miles) and seven known initiation points, so it will be likely to show a high number of ice events by analyzing discharge records. Reach 3 has the largest incremental drainage area (87,200 square miles) and only one known jam initiation point and should result in few ice events by analysis of discharge records. The ice data sheets may also underestimate ice events, particularly in the upstream reaches and other locations where there are few observation sites.

Ice events have been recorded by both methods in all reaches (Fig. 5). The analysis of discharge records resulted in a substantially larger number of ice events than were recorded on the ice data sheets, except in reach 6. The Atchison Bend jam, which forms nearly every year in a highly visible location, is largely responsible for the high number of ice events in reach 6 recorded on the ice data sheets. Reach 6 also has the most detailed observations of the locations of the upstream edge of the ice cover and is probably the area of the most reliable data on the ice data sheets. Because of the disparity in the number of ice events identified by the two methods, it seems best to use the ice data sheets for location of jam initiation points, progression and regression rates, and verification of the ice events identified in the discharge analysis in easily observed areas (such as reach 6).

The largest number of ice events recorded using the discharge records are in reaches 2 and 7 and the least in reach 3. Figure 6 shows the incremental increase in the number of dips by reach; that is, the amount by which the number of dips in a particular reach exceeds that of the previous reach. This figure reveals that dips are likely to initiate in reaches 1, 2, 4, and 7. These reaches coincide with areas characterized by low velocity during winter discharge levels. As pointed out earlier, ice events occurring in reaches 1 and 2 present

the most potential problems, since dips present in these reaches tend to travel downstream, and the decreased discharge can exacerbate downstream ice jams. Therefore, further study of discharge effects is based on reach 1 data.

STATISTICAL ANALYSIS OF WEATHER DATA

The daily average air temperatures for the winter season months October to March were collected from 13 weather stations along the Missouri River from Sioux Falls, S.D., to St. Louis, Mo. (see Table 3 and Fig. 7). The data were collected by water years for the period 1950–1989.

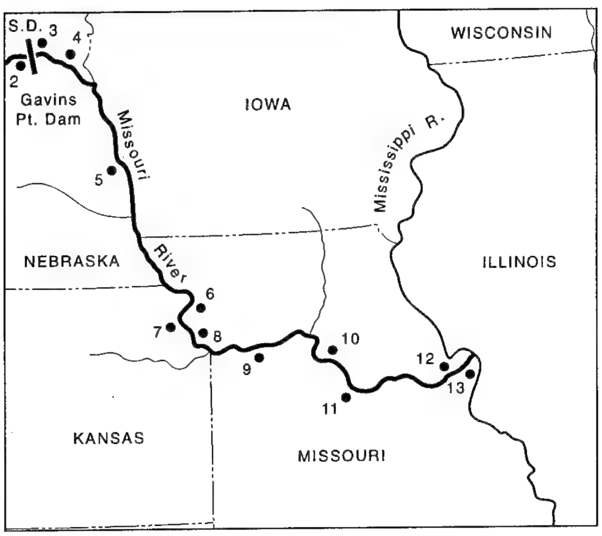


Figure 7. Location map of weather stations used in temperature analysis.

For each winter month at each station, the cumulative freezing-degree-days (FDD) over 1, 2, 3, 5, and 10 consecutive days were calculated and ranked in increasing order of magnitude over the 40-year record. The cumulative freezing-degree-day in °C is defined by

$$\mathrm{FDD}_n = \sum_{i=1}^{n} (T_o - T_i) \qquad (1)$$

where n = number of consecutive days (1 to 10)
T_o = freezing temperature of water (0°C)
T_i = average air temperature on day i (in °C).

For each month, each station, and accumulation period (1, 2, 3, 5, and 10 days), the calculated FDD_n was plotted on probability paper against its plot-position or exceedance frequency (E) defined as

$$E = \frac{r}{N+1} \times 100 \qquad (2)$$

where N = number of years in period of records (40 years or less if there were missing data).
r = rank of particular value of FDD_n over the period of record (r = 1 to N)

As an example, the particular plots for the month of January at Yankton, S.D., are presented in Figure 8a. Every single such plot (for all months at all stations) could be fitted by a straight line with a correlation

Table 3. Weather stations used in temperature analysis.

	Station	*River mile*
1.	Sioux Falls	—
2.	Gavins Point Dam	811
3.	Yankton	806
4.	Vermillion	773
5.	Nebraska City	562
6.	St. Joseph	448
7.	Atchison	422
8.	Kansas City, Mo.	366
9.	Lexington	317
10.	Booneville	197
11.	Jefferson City	144
12.	St. Charles	28
13.	St. Louis	18

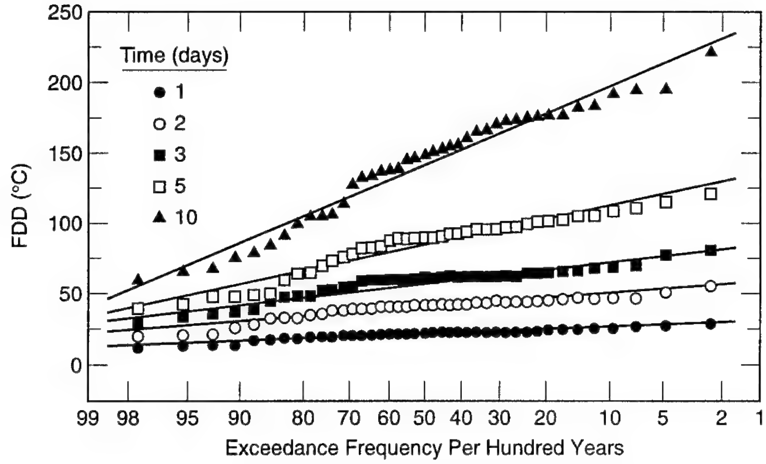
Table 4. Characteristics of normal distribution function of freezing-degree-days at Yankton, S.D.

a. Mean FDD (°C)

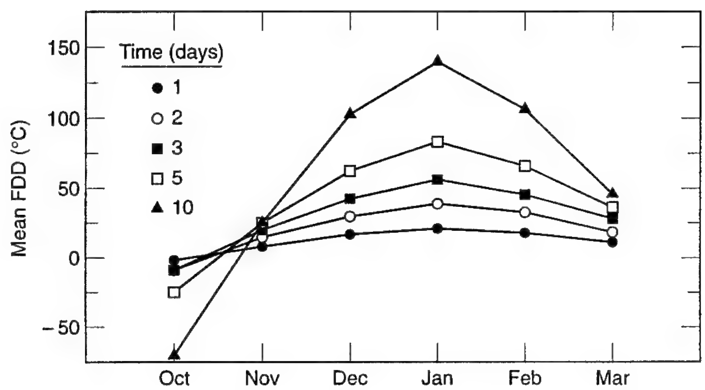
	Duration (days)				
Month	*1*	*2*	*3*	*5*	*10*
October	–0.6	–3.7	–8.8	–22.9	–68.9
November	9.5	16.5	21.1	25.5	25.6
December	18.0	31.8	43.2	63.2	104.2
January	21.9	40.9	57.1	84.3	140.8
February	18.4	34.0	46.4	66.4	106.9
March	11.4	20.6	27.4	37.8	48.0

b. Standard deviation (°C)

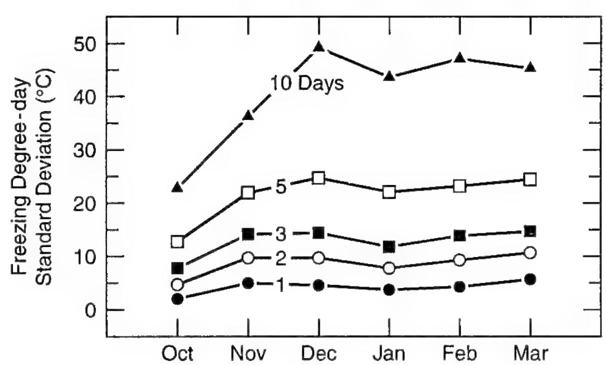
	Duration(days)				
Month	*1*	*2*	*3*	*5*	*10*
October	2.5	5.2	8.1	12.9	22.8
November	5.1	9.8	14.3	22.1	36.4
December	4.8	9.7	14.5	24.8	49.0
January	3.9	7.9	11.8	21.7	43.5
February	4.5	9.2	13.5	23.1	46.6
March	5.5	10.5	14.8	24.3	44.9



a. Freezing-degree-days exceedance frequency distribution.



b. Monthly variation of mean FDD for selected durations.



c. FDD standard deviations for selected durations.

Figure 8. Sample weather statistics, Yankton, S.D.

coefficient of 0.95 or greater. Therefore, in all cases FDD_n can be said to follow a standard normal probability distribution function. This function is characterized by a mean and a standard deviation.

The mean and standard deviations of FDD_n for all stations, the six winter months, and the five selected durations (namely 1, 2, 3, 5, and 10 days) were then calculated by fitting a normal probability distribution function through the data. They are presented in tabular and graphical form in the appendix. As an example, the particular values of mean and standard deviations for Yankton, S.D., are listed in Table 4 and shown in Figure 8b and 8c. The mean FDD is a measure of the average severity of cold weather over the past 40 years, the period of record. The standard deviation represents a measure of the fluctuation in weather conditions at a particular site during the 40 years of record. For example, from Table 4, it can be inferred that in January the coldest daily average temperature in the Yankton area will

be on the order of –21.9 ± 3.9°C (–7.5 ± 7°F) and that a period of 10 consecutive days of cold weather averaging –14.1 ± 4.3°C (6.6 ± 7.7°F) is the norm.

It should be noted that negative values of cumulative freezing-degree-days FDD_n indicate that the average air temperature during the corresponding n consecutive days was above freezing.

STATISTICAL ANALYSIS OF THE ICE-IMPACTED DISCHARGE DATA

During periods of intense cold weather, the production of ice on the Missouri River can cause reductions in discharge in the river that can have tremendous negative impacts, primarily by exposing important water intakes along the river. In this section we will investigate the occurrence of the ice-impacted discharge periods. We will do this statistically, by describing the exceedance probability of the maximum discharge deficits caused by ice. We can determine the exceedance probabilities on an annual basis or on a half-month basis through the winter months of December, January, and February. We can also describe the exceedance probability on the basis of other periods of time, in this case defined by time required to accumulate a determined amount of freezing-degree-days. The half-month basis is valuable for planning future discharges. If the probability of a certain deficit is known, the risk of maintaining low discharge levels can be assessed and the amount of water required carefully assigned. The accumulated freezing-degree-day (AFDD) approach is valuable for providing guidance during the course of winter. During the winter period, the number of accumulated freezing-degree-days can be tracked, and the probabilities of a particular discharge deficit being exceeded can be determined on an updated basis.

Background

In outline, the following sequence of events leads to the occurrence of discharge deficits.

First, there is an intense cold period. This causes a large heat transfer rate from the water surface to the atmosphere. While the heat transfer rate from the water surface is a function of many parameters, including wind speed, relative humidity, long and shortwave radiation, as well as air temperature, it has been found that, during the winter period, heat transfer from the water surface is very well correlated with the difference between the air and water temperature (Ashton 1988). Therefore, we can characterize the intense cold periods simply on the basis of air temperature. A complete analysis of air temperature was performed in the previous section of this report.

During the periods of intense cold, the water cools rapidly. When the water temperature cools to 0°C (32°F), ice begins to form in the river. Observations show that this ice forms as frazil or skim ice that moves in the downstream direction. The moving ice collects into large pans as it travels. As long as the ice is in motion, it will have a negligible impact on the discharge. At some point, the ice may bridge or arch across the river and its motion will be arrested. This may occur in bends, at islands, in slow-moving reaches, or at other points. Moving ice collects at the upstream edge of the stationary ice, and the stationary cover progresses upstream. The presence of a stationary cover changes the hydraulic conditions of the channel dramatically from those of an open channel. By presenting an additional stationary boundary, the ice cover makes a portion of the channel unavailable for flow, changes the channel wetted perimeter and hydraulic radius, and adds additional roughness. The change in the hydraulic radius is quite significant. For wide channels, the hydraulic radius is essentially reduced by half (Wuebben 1986). The net effect is that the relation between the ice cover depth, D_I, and the open water depth, D_o, becomes

$$D_I = 1.32 D_o \left(\frac{N_I}{N_o}\right)^{0.6} \tag{3}$$

where N_I is the effective Manning's roughness of the ice-covered channel, and N_o is the Manning's roughness of the open channel. Carey's (1966) calculations indicate $0.73 < N_I/N_o < 1.37$ such that:

$$1.09 < \frac{D_I}{D_o} < 1.59 \tag{4}$$

Equations 3 and 4 are valid only for the case of constant discharge. In the case of the Missouri River, we can imagine the ice cover progressing upstream in short lengths, ΔX. The depth of each section is initially D_o, the open water elevation. The water level of each section must rise to the new elevation, D_I. By mass conservation we can state

$$Q_{IN} - Q_{OUT} = B\frac{\Delta d}{\Delta t}\,\Delta X \tag{5}$$

where Q_{IN} = flow into the section
Q_{OUT} = flow out of the section
B = river width
Δd = rise in water level over time Δt.

Rearranging

$$Q_{OUT} = Q_{IN} - B\frac{\Delta d}{\Delta t}\Delta X \tag{6}$$

we see that the flow out of the reach will be less than the flow in as long as the water level is rising. As the water level rises in response to the presence of the stationary ice cover, the discharge downstream of the location where the ice cover initially arches must be reduced. This reduction will occur as long as the ice cover is progressing upstream and the water level under the cover is increasing in elevation.

The impacted discharges can be expected whenever a stationary ice cover in the Missouri River is progressing upstream. We would expect ice-impacted discharges to occur only during or immediately following cold periods when ice was generated in the open water areas of the river. Once a stationary ice cover has formed, further growth in thickness of the ice has a minimal impact on the water level. The magnitude of discharge deficit can be estimated in the following manner. We rewrite eq 6 so that

$$Q_{DIFF} = Q_{IN} - Q_{OUT} = B\,(D_I - D_o)\,V_I \tag{7}$$

where V_I is the progression rate of the ice cover, which can be estimated as

$$V_I = \frac{C_o V_a}{1-e} \tag{8}$$

where C_o is the volumetric concentration of the ice arriving at the leading edge of the stationary ice cover, e is the porosity of the stationary cover, and V_a is the mean arrival velocity. Unfortunately, the value of these parameters can only be roughly estimated at this time. We can see that the ice cover progression rate is strongly proportional to the concentration of the arriving ice. The ice concentration in turn is a strong function of the heat transfer rate from the water surface. We would expect that V_I is at a maximum when C_o is at its maximum, and we would expect that the maximum impact on the discharge would occur during the intense cold periods, when the maximum heat transfer rates occur.

In the remainder of this section we will select a reach in which the ice-impacted discharge periods are easily identified, then we will determine all of the impacted discharge periods over a suitable length of record. Next we will statistically analyze the maximum ice-caused discharge deficits on an annual, half-month, and accumulated freezing-degree-day (AFDD) basis.

Selection of initial reach for study

The ice-impacted discharge periods can be identified by comparing the discharges recorded at the upstream and downstream end of a specific reach. If the upstream discharges are relatively constant and unaffected by ice, this increases the ease with which the comparisons can be made. The most appropriate reach then is the most upstream reach in the study area, from Yankton to Sioux City, because the flow at Yankton reflects the discharge released at the Gavins Point Dam, approximately 5.3 miles upstream. The releases at Gavins Point Dam are not affected by ice in the Missouri River.

Determining the ice-impacted discharge periods

Generally, the flow at Yankton follows a consistent pattern during the winter months. During November and the earliest part of December the flow at Yankton is declining until a stable level is reached and maintained for the remainder of December, January, and February. There can be some small fluctuations in the flow at Yankton during this time, but historically the flow is maintained at a fairly constant level. The ice-impacted discharge periods are determined by comparing the discharge at Yankton and Sioux City. Ideally, the flow at Yankton should be numerically "routed" to Sioux City and this routed flow compared to the flow measured at Sioux City. However, because of the very steady nature of the flow at Yankton, the relatively close spacing of both stations (70 miles), and the fact that only daily average discharges were available, flow routing was found not to be necessary. The ice-impacted discharge periods were determined by subtracting the discharge at Sioux City from that at Yankton each day. Those days when the results were positive were then selected as the ice-impacted discharges. This was done for all winters from 1970–71 through 1987–88. The resulting data, listed in Table 5, are the date on which the maximum discharge deficit occurred (that is, the largest difference between the Sioux City gage and the Yankton gage), the magnitude of the discharge deficit, the length of the impacted discharge period in days, and the accumulated freezing-degree-days (°C) from 1 December at the time of the maximum discharge deficit. There are 65 recorded periods of discharge deficits.

Statistical analysis of ice-impacted discharges by time period

A histogram of discharge deficit maximums that occurred during the ice-impacted periods is shown

Table 5. Discharge deficit record.

Date	Max deficit (1000 ft³/s)	Length of period (days)	AFDD at max (°C)	Date	Max deficit (1000 ft³/s)	Length of period (days)	AFDD at max (°C)
19 Jan 71	2.5	18	467.8	20 Dec 80	0.7	2	72.5
1 Feb 71	3.3*	5	553.1	2 Feb 81	3.5*	2	258.3
9 Feb 71	1.9	5	657.2	9 Feb 81	2.7	4	323.9
22 Dec 71	0.8	1	151.9	20 Dec 81	0.8	2	90.0
15 Jan 72	5.5*	3	343.3	10 Jan 82	4.0*	3	305.6
20 Jan 72	5.0	10	375.3	18 Jan 82	3.0	4	433.9
10 Feb 72	1.0	10	676.4	24 Jan 82	2.0	3	504.4
15 Feb 72	0.5	2	716.9	5 Feb 82	1.0	4	649.2
18 Feb 72	3.2	2	727.2	18 Jan 83	0.3*	1	135.0
10 Jan 73	0.8*	3	390.0	13 Dec 83	0.3	1	190**
11 Jan 74	4.0*	14	420.3	22 Dec 83	11.5*	11	370**
4 Feb 74	0.4	2	509.2	6 Feb 84	0.7	1	750**
13 Jan 75	6.2*	4	201.7	25 Dec 84	1.0	1	128.6
6 Feb 75	3.2	3	366.9	30 Dec 84	0.7	1	157.2
17 Dec 75	0.9	1	102.5	2 Jan 85	1.3	2	200.0
8 Jan 76	8.0*	7	289.2	12 Jan 85	0.8	2	277.8
17 Jan 76	1.7	1	367.2	15 Jan 85	1.0	2	303.6
27 Jan 76	0.3	1	420.8	21 Jan 85	2.6	4	363.9
5 Feb 76	2.6	4	455.8	31 Jan 85	4.0*	16	457.8
11 Dec 76	0.6	1	111.1	25 Dec 85	4.1*	3	296.4
21 Dec 76	0.8	1	126.1	29 Dec 85	0.7	2	322.2
18 Jan 77	0.3	1	480.6	7 Jan 86	3.1	3	382.2
30 Jan 77	4.0*	7	579.4	27 Jan 86	0.7	1	407.2
6 Dec 77	4.6*	6	26.9	11 Feb 86	1.2	6	482.5
2 Jan 78	0.6	1	235.6	21 Feb 86	1.3	2	570.0
9 Jan 78	0.7	1	323.6	5 Jan 88	7.4*	11	132.8
17 Jan 78	1.0	2	466.4	13 Jan 88	2.0	2	263.9
28 Jan 78	1.0	2	650.3	21 Jan 88	1.4	4	311.9
25 Jan 79	2.5*	9	610.8	26 Jan 88	0.8	1	363.6
8 Jan 80	6.8*	2	101.9	2 Feb 88	0.8	2	424.2
10 Jan 80	0.3	1	135.3	8 Feb 88	0.5	2	519.4
12 Jan 80	1.2	1	152.5	13 Feb 88	0.5	2	599.7
29 Jan 80	0.9	5	226.9				

* Annual maximum
** Estimated

in Figure 9. It can be seen that nearly half the maximum deficits were 1000 ft^3/s or less. The annual maximum return interval can be found by selecting the maximum discharge deficit that occurred during each winter. The return interval is found by assigning each maximum discharge deficit a probability, P, defined by $J/(N+1)$, where J is the rank of the deficit and N is the total number of data points available. The return interval is then $1/(1-P)$. The annual maximum return interval is shown in Figure 10. It can be seen that the distribution is nearly normally distributed, and that there is one apparent outlier. This outlier occurred on 22 December 1983 and has a value of 11,500 ft^3/s. This is by far the largest ice-impacted discharge deficit recorded during the period of record.

The discharge deficit record can be further analyzed by grouping the recorded discharge deficits into half-month periods, as shown in Table 6. It can be seen that impact periods do not occur every year during each half month. The most likely half months are 16–31 December (61%), 1–15 January (55%) and 16–31 January (61%). Again, the return interval for each half-month period is found in the same manner as the annual maximum return interval. The annual maximums occurring in each half-month period are shown in Figures 11 through 14. The periods 1–15 December and 16–28 February were not plotted because there were too few data points. We can see that, in large part, the data are normally distributed except for the period 16–31 December. The data for this period seem to suggest

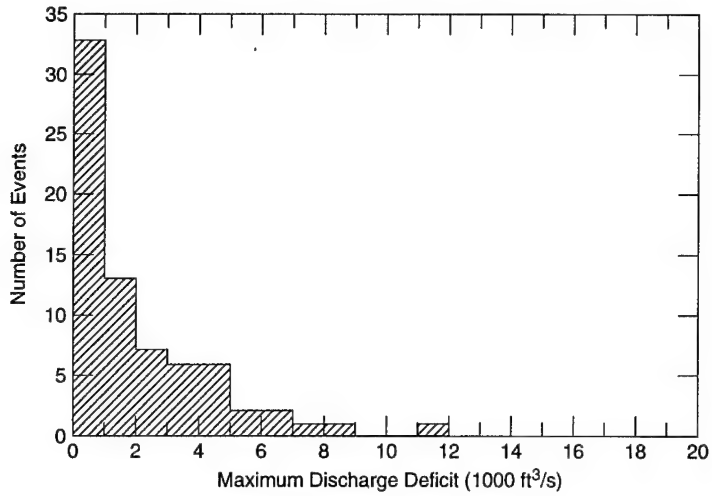


Figure 9. Histogram of discharge deficit maximums, Yankton to Sioux City.

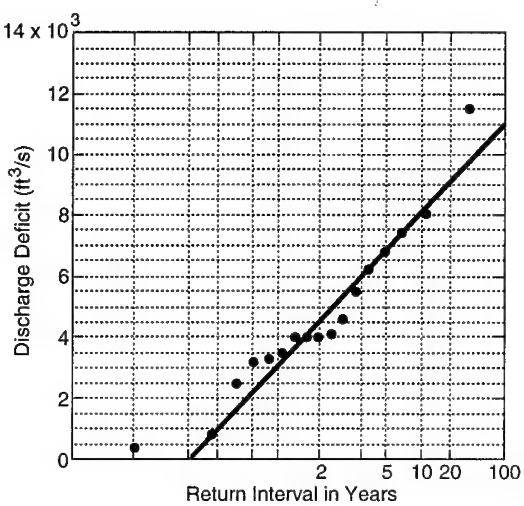


Figure 10. Return interval of the annual maximum discharge deficit.

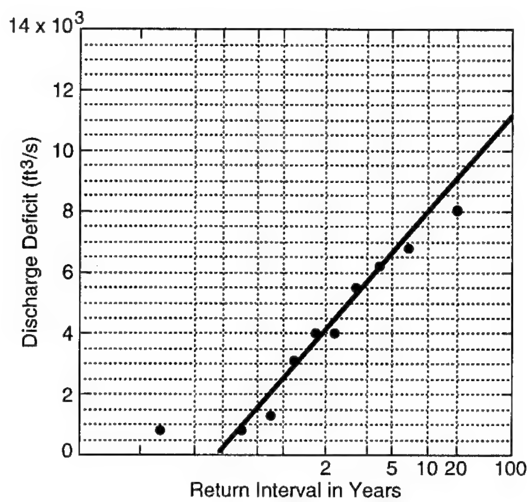


Figure 12. 1–15 January probabilities.

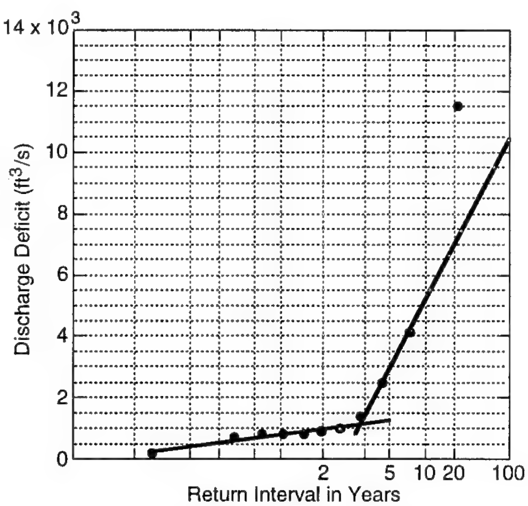


Figure 11. 16–31 December probabilities.

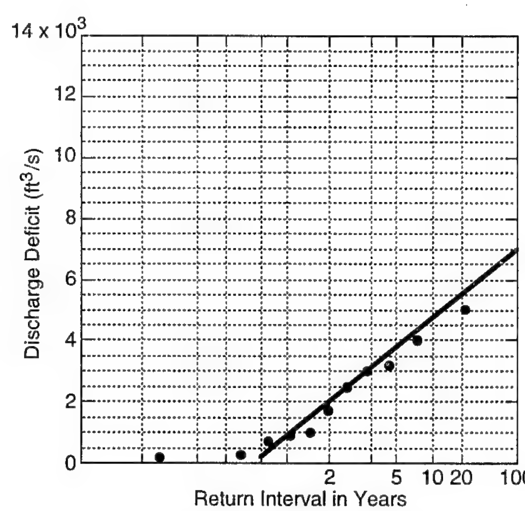


Figure 13. 16–31 January probabilities.

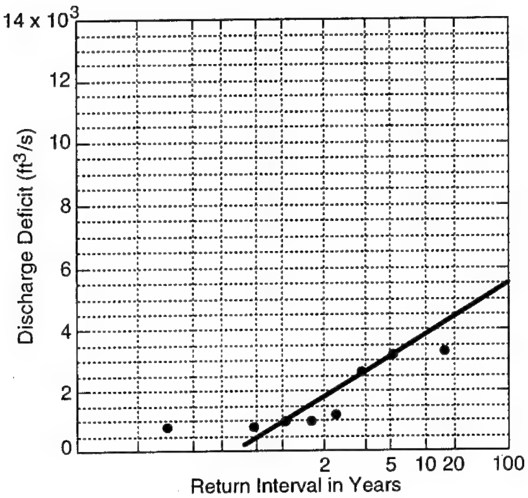


Figure 14. 1 –15 February probabilities.

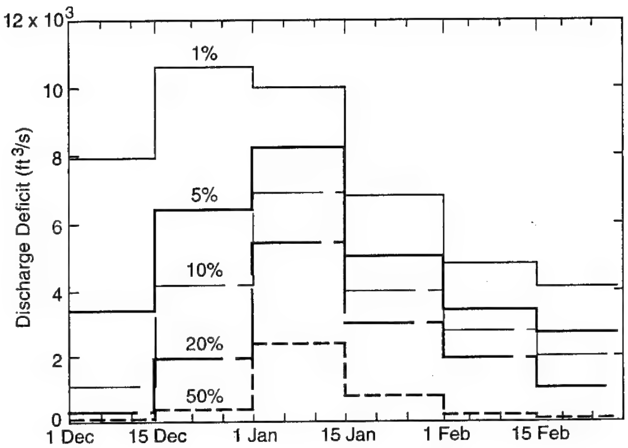


Figure 15. Probability of discharge deficit by time period.

Table 6. Discharge deficit by half-month periods, winter 1970–71 through 1987–88.

	1–15 Dec	*16–31 Dec*	*1–15 Jan*	*16–31 Jan*	*1–15 Feb*	*16–28 Feb*
Years with ice-impacted period	4	11	10	11	8	4
Total ice-impacted periods	5	15	17	17	13	5
Percentage of years with ice-impacted period	22	61	55	61	44	22
Years in which annual maximum occurred	2	3	7	3	1	1

a mixed population, and separate probability curves have been drawn to indicate the two populations. At this time it is not possible to explain the mixed-population appearance of this data.

To complete the statistical analysis, we must take note that discharge deficit cannot be expected during each half-month period every winter as shown in Table 6. We can find the conditional probability by multiplying the percentage of years in which an ice-impacted period occurred by the exceedance probabilities associated with the return intervals shown in Figures 11 through 14. These conditional probabilities define the risk of a particular ice-impacted discharge deficit being exceeded in any year. The results are shown in Figure 15. To determine the conditional probabilities for the period 1–15 December, the excedance probabilities in Figure 11 (16–31 Dec) were used, but these probabilities were multiplied by 22%, the percentage of years in which a discharge deficit occurred during the period 1–15 December. To determine the conditional probabilities for the period 16–28 February, the probabilities in Figure 14 (1–15 Feb) were used, but they were multiplied by 22%, the percentage of years in which a discharge deficit occurred during the period 16–28 February.

Statistical analysis of ice-impacted discharges by accumulated freezing-degree-days

The number of freezing-degree-days for any day is defined by difference in the average daily air temperature and 0°C (32°F). For example, if the daily average air temperature is –10°C (14°F), this would translate into 10 freezing-degree-days (°C-day) for that day. We can characterize a winter by the number of freezing-degree-days that are accumulated during the winter. In this study, we accumulate the freezing-degree-days starting on 1 December. Therefore, we can define the accumulated freezing-degree-days (AFDD) on any day as the number of freezing-degree-days accumulated between 1 December and that day. A plot of the exceedance probabilities of AFDD for Yankton, S.D., is shown in Figure 16. The probabilities are shown for the dates 1 December, 15 December, 1 January, 15 January, 1 February, and 15 February.

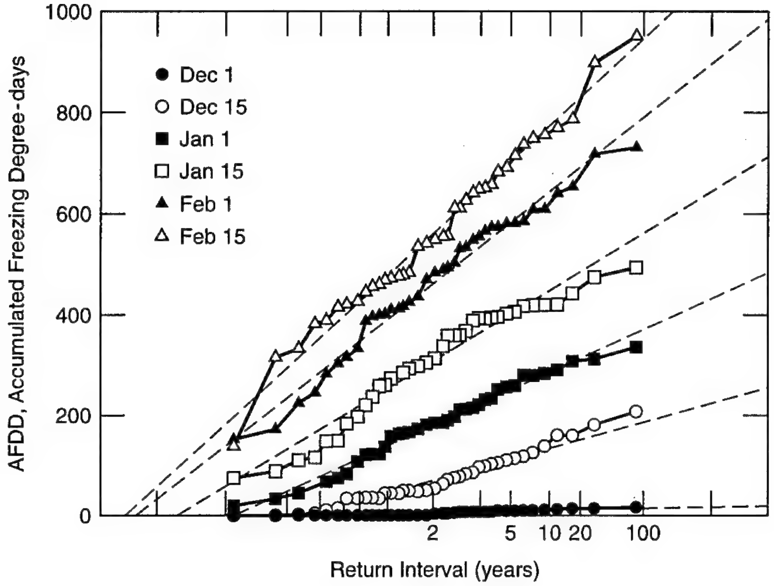


Figure 16. Yankton accumulated freezing-degree-days (December 1 start date).

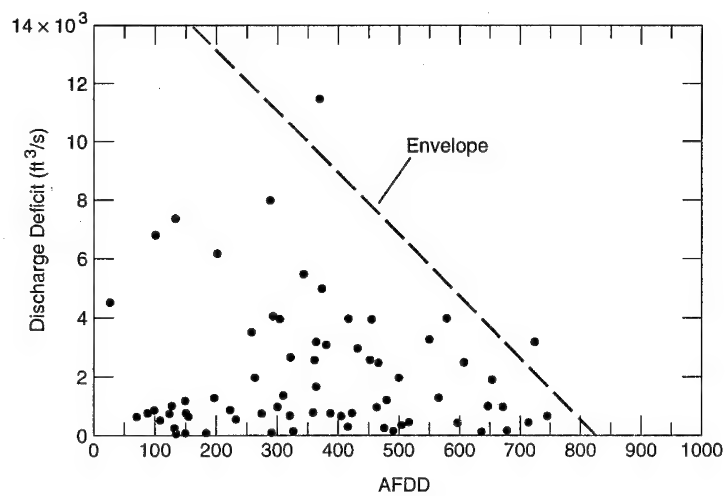


Figure 17. Maximum discharge deficit vs. AFDD (Yankton).

In Figure 17 the maximum discharge deficits listed in Table 5 are plotted against the AFDD that occurred on the day that the maximum discharge deficit occurred. It can be seen that in general there is an "envelope" that describes the limit of the discharge deficit and that the upper limit of this envelope decreases with increasing AFDD. This decrease reflects the fact that as each winter progresses (and the number of AFDD increases), the amount of ice in the river is increased and the amount of open water decreased. With the reach fully ice covered, discharge deficits should not occur.

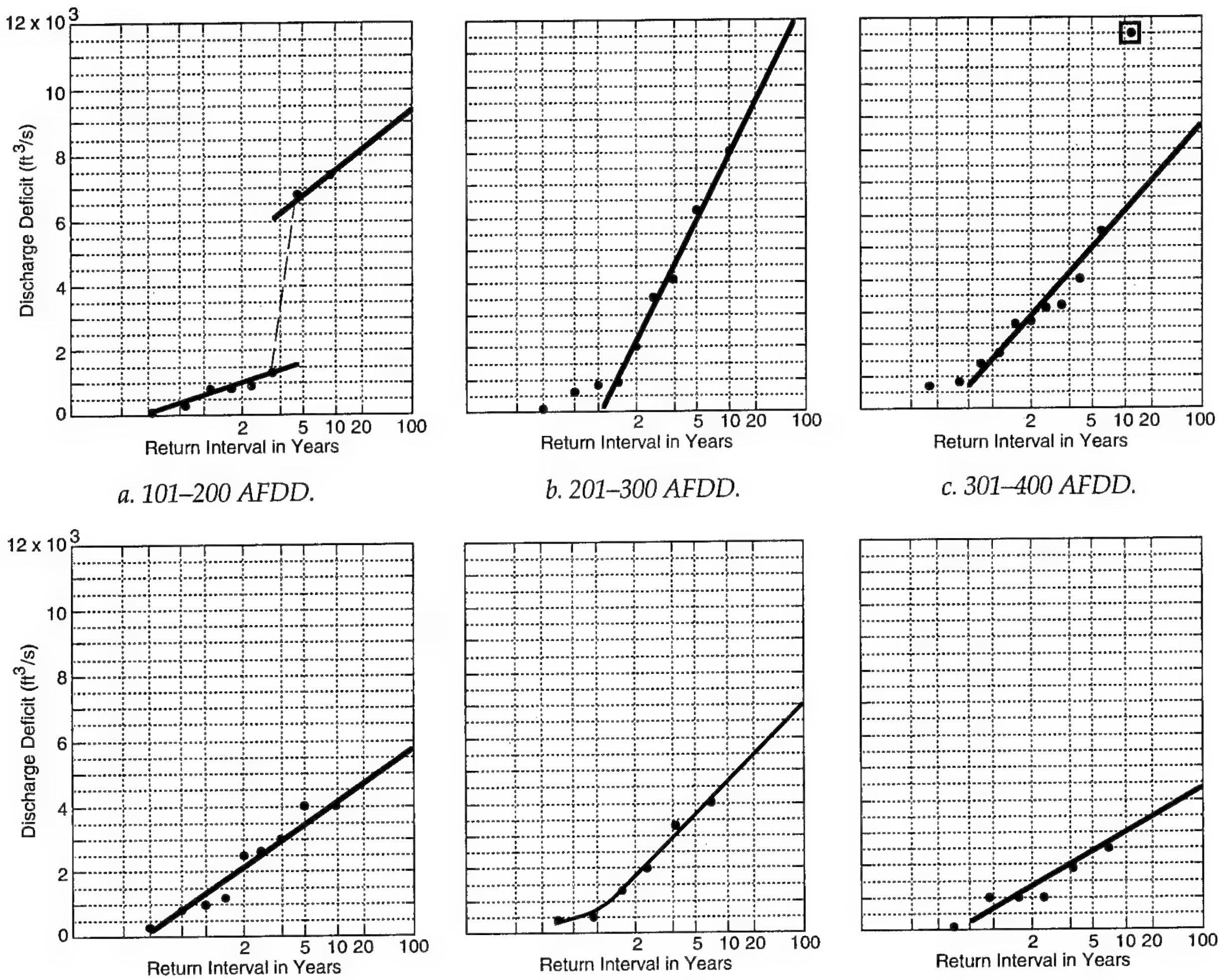
To complete this analysis, we can group the discharge deficits into AFDD categories as shown in Table 7. It can be seen that not every AFDD category is reached every year and that ice-impacted periods do not occur every year during each AFDD category that is reached. The annual maximum discharge deficits occurring in each AFDD category are shown in Figure 18. As with the previous statistical analysis, the return interval for each AFDD category is found by assigning each maximum discharge deficit a probability, P, defined by $J/(N+1)$, where J is the rank of the deficit and N is the total number of data points available. The return interval is then $1/(1-P)$. We can see that, in large part, the data are normally distributed except for the category 100–200 AFDD. This category is somewhat comparable to the time period 16–31 December. As with that time period, the data for this category suggest a mixed population, and separate probability curves have been drawn to indicate the two populations. At this time it is not possible to explain the mixed population appearance of this data.

To further extend the statistical analyses, we must take note that discharge deficit cannot be ex-

pected during each AFDD category every winter as shown in Table 7. We can find the conditional probability of exceedance by multiplying the percentage of times that ice-impacted periods occurred during the AFDD category by the exceedance probabilities associated with the return intervals in Figure 18. These new probabilities define the risk of a particular ice-impacted discharge deficit being exceeded in any year in which that AFDD category is reached. The results are shown in Figure 19.

Table 7. Discharge deficit by AFDD periods, winter 1970–71 through 1987–88.

	0–100	*101–200*	*201–300*	*301–400*	*401–500*	*501–600*	*601–700*	*>700*
Years in which AFDD category reached	18	18	17	16	15	13	9	5
Years with ice-impacted period	4	8	9	11	9	6	6	2
Total ice-impacted periods	4	14	9	16	12	7	7	3
Percentage of years in which impacted period occurred during AFDD period.	22	44	53	69	60	46	66	40



a. 101–200 AFDD. *b. 201–300 AFDD.* *c. 301–400 AFDD.*

d. 401–500 AFDD. *e. 501–600 AFDD.* *f. 601–700 AFDD.*

Figure 18. Accumulated freezing-degree-day probabilities.

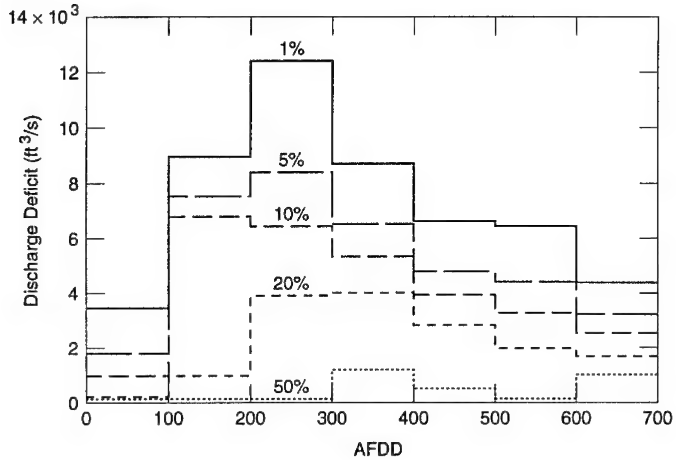


Figure 19. Discharge deficit risk associated with AFDD probabilities.

CORRELATION OF ICE-IMPACTED DISCHARGE AND RIVER STAGES

Baseline flows

While the objective of the study is to determine the required releases from Gavins Point Dam to ensure adequate flows for water intakes downstream, the performance of those intakes is dependent not only on those releases but also the incremental discharge entering the river from tributary sources. When determining an appropriate release in anticipation of a cold weather period in the near future, decisions can be based on the water levels and flows in the river at the time of its occurrence. However, long-term planning efforts must rely on predicted flow distributions.

For each of the 10 discharge gaging stations listed in Table 1, mean daily flow information was sorted by month to determine representative variations in flow along the river. That is, for a given gaging station, say Yankton, and a given month, say January 1970, all of the mean daily flows were averaged to come up with a mean monthly daily flow. The mean flows for all months of January from 1955 through 1988 at that station were likewise determined, and then averaged to determine a mean of the mean monthly discharges for all January flows at Yankton. The starting year of 1955 was selected, as that was the year storage behind Gavins Point Dam was first available for regulation of downstream flows. Monthly mean discharges prior to 1955 were normally much lower during winter months.

This averaging process was repeated for all months between October and March and for all 10 gaging stations. The results of this process for the months of December through March are presented in Table 8. This information is also presented graphically in Figure 20 in terms of discharge variation with drainage area below Gavins Point Dam. Discharge measured at Yankton is considered equivalent to releases from the dam. For comparison, an actual, single-day flow distribution from a low flow period in January 1970 that had the same Gavins Point release as the long-term mean-of-means is included in both Figure 20 and Table 8. A comparison of this single-day flow distribution with that of the January mean-of-means distribution shows good correlation.

Since the release from Gavins Point Dam is not directly coupled to inflows elsewhere in the river downstream, those releases have been assumed to constitute an independent variable, distinct from inflows elsewhere in the system. Under this assumption, whether 1,000 or 30,000 ft^3/s was to be released from Gavins Point, downstream incremental inflows would remain unchanged. Therefore, in Table 9 the Yankton discharge for each month shown in

Table 8. Mean monthly discharge distributions.

Station	River mile	Discharge (ft^3/s), mean of means December	January	February	March	Q (ft^3/s) Jan 70
Yankton	805	17,500	15,000	14,600	18,600	15,000
Sioux City	732	18,400	15,600	15,700	22,000	16,500
Omaha	616	20,000	16,700	18,700	26,900	17,000
Nebraska City	562.6	24,500	20,200	25,500	37,500	19,000
Rulo	498	26,000	21,300	27,100	40,700	19,700
St. Joseph	448	28,200	23,100	30,000	45,000	20,750
Kansas City	366.1	33,200	27,000	36,500	54,525	25,000
Waverly	293.5	34,100	27,900	37,600	55,000	25,500
Booneville	196.6	41,000	33,200	46,500	69,500	34,800
Hermann	97.9	58,100	46,400	64,600	96,000	40,000

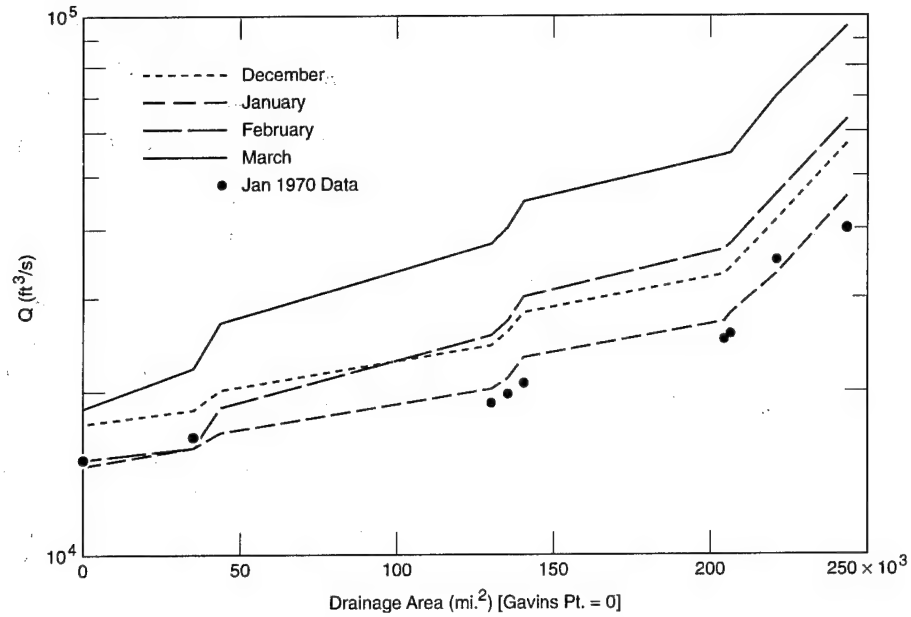


Figure 20. Mean monthly discharge distributions.

Table 8 has been subtracted from the discharges at the other stations. Any planned release would then simply be added to the values for the applicable month in Table 9 to find a representative flow distribution along the river.

Minimum flow requirements

To estimate flows necessary to ensure adequate water surface elevations at municipal and industrial (M&I) water intakes along the river, MRD personnel conducted a survey of all known intakes.* Among the information solicited in this survey were estimates of the minimum stage necessary for normal intake operation and the critical stage at which the intake would be effectively shut down. The water surface elevation information obtained in this survey, presented in Table 10, was used as the basis for estimating the discharge magnitudes necessary for water intake operations.

To estimate the discharge distributions required to satisfy water users along the river, the information in Table 10 was compared with the results of a water surface profile analysis by MRD personnel† using the HEC-2 computer program (USACE 1990).

* W. Stern, CEMRD-ED-TH, 1991, personal communication; minimum flow requirements for water supply, survey and associated analysis conducted in conjunction with Missouri River Master Water Control Manual Review and Update—Phase 2.

† A. Swoboda, CEMRD-ED-TH, 1991, personal communication; verified HEC-2 Water Surface Profile data deck and associated analysis conducted in conjunction with Missouri River Master Water Control Manual Review and Update—Phase 2.

Table 9. Mean monthly incremental discharge distributions.

Station	River mile	Discharge (ft^3/s), mean of means December	January	February	March	Q (ft^3/s) Jan 70
Yankton	805	0	0	0	0	0
Sioux City	732	900	600	1,100	3,400	1,500
Omaha	616	2,500	1,700	4,100	8,300	2,000
Nebraska City	562.6	7,000	5,200	10,900	18,900	4,000
Rulo	498	8,500	6,300	12,500	22,100	4,700
St. Joseph	448	10,700	8,100	15,400	26,400	5,750
Kansas City	366.1	15,700	12,000	21,900	35,925	10,000
Waverly	293.5	16,600	12,900	23,000	36,400	10,500
Booneville	196.6	23,500	18,200	31,900	50,900	19,800
Hermann	97.9	40,600	31,400	50,000	77,400	25,000

Table 10. Minimum required stages and discharges required for water supply.

Plant name	River mile	Critical stage (ft)	Minimum discharge Intake* (ft^3/s)	Minimum discharge Reach (ft^3/s)
Yankton Water	805.90	1150.00	6000	6000
Terra International	718.7		6000	8000
Neal North 3	718.40	1052.50	8000	8000
Neal North 2	718.30	1052.50	8000	8000
Neal North 1	718.30	1052.50	8000	8000
Neal North 4	716.70	1049.50	6500	8000
Blair Water	648.5	981.00	6000	8000
Ft. Calhoun Power	645.90	979.00	6000	8000
Florence Water	626.3	964.70	6000	8000
N. Omaha Power	625.20	963.00	7500	8000
C. Bluffs Water	618.9	957.70	8000	8000
Furfuryl (QuakeB Energy 1 & 2)	606.00	946.00	6000	6000
CB Energy 3	606.00	948.00	6000	6000
OPPD Neb City Power	556.30	896.00	6000	6000
NPPD Cooper Nuclear Power	532.60	869.00	6000	6000
Missouri Amer. Water	452.3	787.50	6000	6000
St. Joseph Power	446.00	787.00	7000	9500
Atchison Water	423.3	763.00	6000	9500
KCPL Iatan Station	411.10	755.00	7000	9500
Leavenworth Water	397.4	740.70	6000	9500
Johnson County Water	379.9	723.50	6000	9500
Nearman Creek Power	378.60	724.00	9500	9500
BPU Quindaro	373.50	717.50	7000	9500
Quindaro Power	373.40	717.50	7000	9500
KCMO Water	370.5	716.30	9500	9500
KCPL Grand (Summer)	365.70		6000	7500
KCPL Hawthorne Station	358.40	704.50	7500	7500
Independence (Stdby)	345.30	693.00	6000	7500
Sibley Power 4	336.40	676.00	6000	7500
Sibley Power 5	336.40	676.00	6000	7500
Lexington Water	317.1	666.30	7000	7500
Glasgow Municipal Water	226.7	592.10	16000	16000
Booneville Water	197.5	566.10	11500	16000
Capital City Water	144.0	519.00	7500	8500
Chamois Power	117.10	492.80	6000	8500
Callaway Nuclear Station	115.50	495.00	8500	8500
Labadie Power Station	57.90	442.00	6000	7000
St. Louis Howard Bend	37.1	420.00	6000	7000
St. Louis Central	36.5	423.00	7000	7000
St. Louis North (west)	20.50	406.00	6000	7000
St. Louis North (east)	20.20	409.00	7000	7000

*Note: A value of 6,000 ft^3/s indicates a required flow of less than or equal to 6,000 ft^3/s. Many sites had stage requirements well below the calibrated range of the hydraulic model.

Using stage-discharge rating curves generated by HEC-2 at each site, it was possible to turn the critical shut-off stages for an intake into a required local discharge. The resulting discharges are shown in Table 10 along with the minimum discharges required to satisfy all water intakes within river reaches defined by two adjacent discharge gaging stations. Discharge requirements listed as being equal to 6,000 ft^3/s include those sites having stage requirements falling below water surface elevations corresponding to the minimum discharge value of 6,000 ft^3/s employed in HEC-2. Extrapolation to these very low stages would be unreliable and is unnecessary for the purposes of this study. These minimum flow requirements are also shown graphically in Figure 21. For the remainder of the report we will use the reach-based minimum flow requirement distribution as a basis for required releases from Gavins Point Dam.

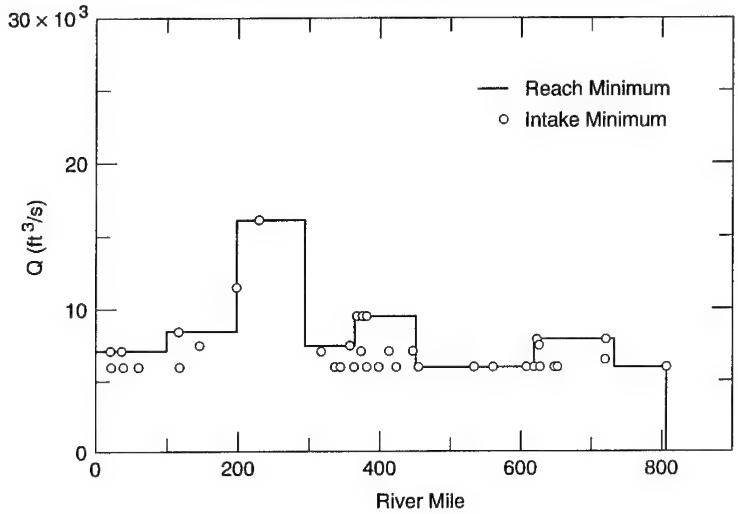


Figure 21. Minimum required discharges for water supply.

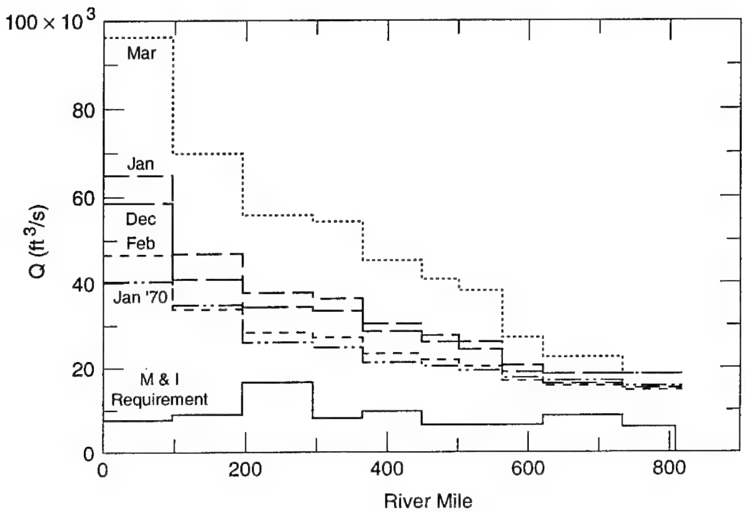


Figure 22. Mean monthly minimum flow requirements.

Comparison of baseline flows with minimum flow requirements

Figure 22 presents a comparison of the long-term, monthly mean discharges with the reach-based minimum flow requirements determined above. Subtracting these minimum flow requirements from the monthly mean discharges provides the long-term average discharge in excess of that required for water supply shown in Figure 23. In this figure, it can be seen that river reaches closest to falling below the minimum required stages are typically between river miles 616 to 806. Further, January is clearly the month of greatest concern from a purely open water hydraulic standpoint, followed by December and February.

If we subtract the minimum excess discharge for each month shown in Figure 23 from the long-term monthly mean release at Gavins Point, the result is a long-term average minimum release from the dam to meet the specified minimum discharge distribution along the river. In Table 11 these minimum excess discharges have been subtracted from all corresponding monthly mean excess discharge values to give not only the minimum release from Gavins Point but also the distribution of flow in excess of that required for water supply at all gaging stations along the river for the case of tributary inflows equal to their long-term averages.

In the Missouri River Master Water Control Manual Review and Update (USACE 1990), under the section on baseline for plan comparison, it is stated that "...the minimum release considered to be applicable at this time is 6,000 cfs. Even though higher releases are currently required to provide water at the intakes downstream from the main stem system, the minimum nonnavigation release baseline will continue to be 6,000 cfs."

Table 11. Monthly minimum release flow distributions.

Station	River mile	Q_{min} M&I (reach)	Minimum monthly flow distributions Dec	Jan	Feb	Mar
Gavins Point	811		7,100	7,400	6,900	6,000
Yankton	805		7,100	1,400	900	0
		6,000				
Sioux City	732		0	0	0	1,400
		6,000				
Omaha	616		3,600	3,100	5,000	8,300
		8,000				
Nebraska City	562.6		8,100	6,600	11,800	18,900
		6,000				
Rulo	498		9,600	7,700	13,400	22,100
		6,000				
St. Joseph	448		8,300	6,000	12,800	22,900
		6,000				
Kansas City	366		15,300	11,900	21,300	34,425
		9,500				
Waverly	293.5		7,700	4,300	13,900	26,400
		7,500				
Booneville	196.6		22,100	17,100	30,300	48,400
		16,000				
Hermann	97.9		40,700	31,800	56,900	76,400
		8,500				
St. Louis	0		40,700	31,800	56,900	76,400
		7,000				

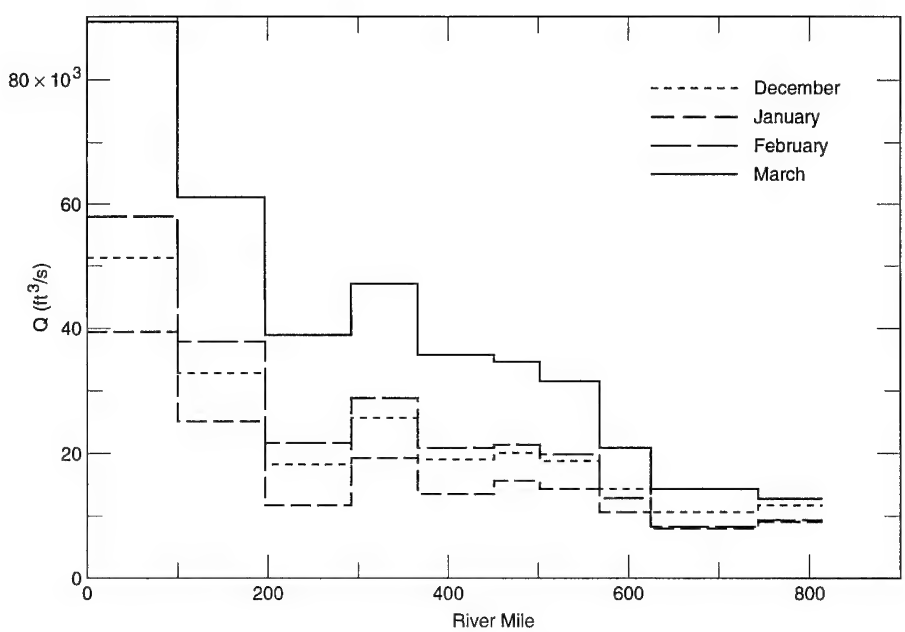


Figure 23. Excess mean monthly discharge.

At least for the case of tributary inflows downriver being at or below their long-term averages, a Gavins Point release of 6,000 ft^3/s would be clearly insufficient for most winter months—even in the absence of ice. As shown in Table 11, the lowest acceptable long-term average release would be approximately 6,000 ft^3/s in March. Although not shown in Table 11, the minimum releases for the months of October and November would be 7,200 and 7,100 ft^3/s, respectively. January would require the greatest release from Gavins Point at 7,400 ft^3/s, but downstream tributary inflows that differ from the long-term means could of course change the value during any specific event.

DETERMINATION OF REQUIRED RELEASES IN WINTER

Two basic approaches for the determination of required releases due to ice impacts have been developed. The first is based on long-term statistics and would be appropriate for annual or long-term planning when little is known about weather and runoff conditions to be expected. The second approach is targeted at determining an appropriate short-term response to an anticipated cold weather–ice event.

Long-term planning approach

This approach would be applicable for developing a general operating plan or an annual operating plan when little information is available on water supply and weather to be encountered. It relies on the long-term average incremental discharges developed earlier and statistical representations of weather patterns to provide a suggested release schedule from Gavins Point Dam.

In the section of the report dealing with a comparison of baseline flows with the minimum flows required for water intake operation, minimum releases from Gavins Point Dam during the winter months were developed assuming no ice effects. As shown in Table 11, these minimum releases varied from a low of 6,000 ft^3/s in March to a high of 7,400 ft^3/s in January. Those values can be used in conjunction with the information presented in Figure 15 on the probable magnitude of discharge deficit events during each 2-week time period throughout the winter for various levels of risk. The result is presented in Figure 24, which provides recommended minimum releases throughout the winter season.

To use this information, it is merely necessary to select an acceptable value of risk and read the discharges corresponding to that risk line on the plot. For example, to protect against 5-year recurrence in-

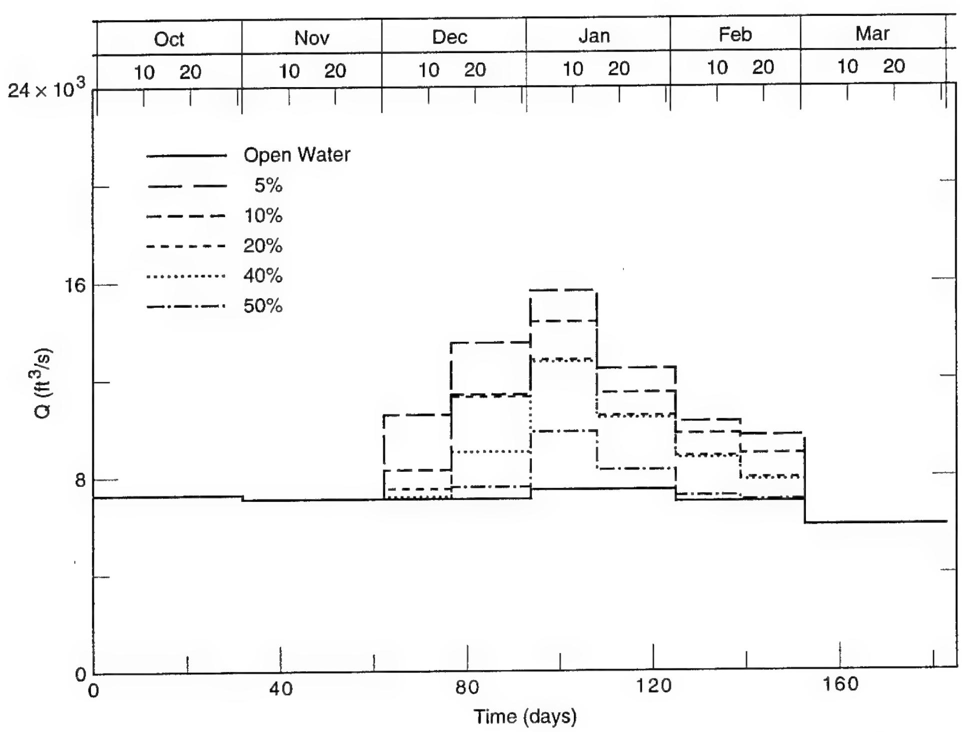


Figure 24. Minimum release from Gavins Point Dam (ice-impacted flows).

terval events the user would follow the 20% chance line to come up with minimum recommended releases. Similar information for the primary ice event months of December through February is also provided in Table 12.

Table 12. Minimum releases from Gavins Point Dam for ice-impacted flows.

	December		*January*		*February*	
Risk	*1–15*	*15–31*	*1–15*	*15–31*	*1–15*	*15–28*
Open water	7,100	7,100	7,400	7,400	6,900	6,900
50%	7,200	7,500	9,800	8,200	7,100	7,000
20%	7,400	9,000	12,800	10,400	8,800	7,900
10%	8,200	11,300	14,300	11,400	9,700	8,900
5%	10,500	13,500	15,600	12,400	10,300	9,600

This approach could also be modified to address releases during a specific year. It would still be based on long-term weather statistics, but could allow consideration of years that are relatively wetter or drier than normal. If information was available on expected tributary inflow rates, the monthly minimum release flow distributions, such as those presented for long-term averages in Table 11, could be calculated for specific time periods. Combining this with the discharge deficit probability information contained in Figure 15 would provide recommended release information similar to that in Figure 24, but tailored more to the inflow conditions expected for a given year.

Short-term approach

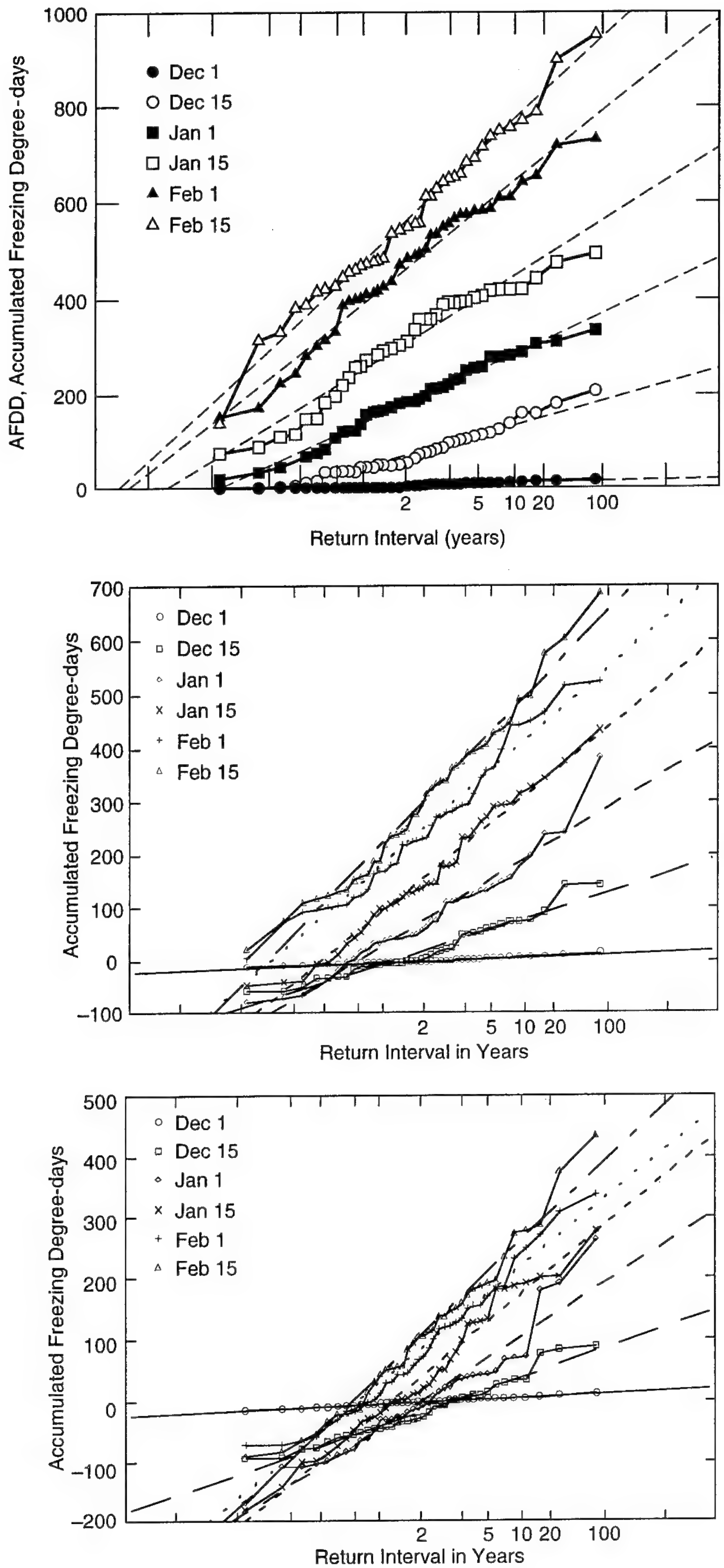
This approach would be applicable for near-term modification of the planned winter release schedule in anticipation of an approaching cold weather period. As in the long-term approach just discussed, the estimation of required releases from Gavins Point is again based on an acceptable level of risk. Since the travel time of releases from Gavins Point Dam to many of the water intakes is significantly longer than the time period of reliable weather forecasts, winter releases must be based on probabilistic, conservative estimates of required flows.

To use this approach it is first necessary to estimate the potential severity of the event. The probable level of discharge deficit can be determined from either Figure 15 or Figure 19. The most straightforward approach is to use Figure 15, which provides the probable level of discharge deficit corresponding to a selected level of risk based on calendar date. Thus, a 10% chance of exceedence on, say, 23 December would give an estimated discharge deficit of 4,200 ft^3/s, whereas on 23 February it would be only 2,000 ft^3/s. This estimated deficit could then be coupled with current known (or projected) levels and flows to determine whether such a deficit might create a problem and if so, how much the Gavins Point discharge should be increased.

For example, using the long-term monthly mean incremental discharge distributions in Table 9, an assumed Gavins Point discharge of 10,000 ft^3/s, and further assuming that it is 3 January, we could estimate that there is a 10% risk of discharge deficit of 6,900 ft^3/s or greater occurring. Since the discharge in reach 2 would be 10,600 ft^3/s, and the minimum required reach flow is 8,000 ft^3/s, the discharge from Gavins Point would have to be increased by 4,300 ft^3/s to avoid difficulty in that reach. Further, since the water travel time from Gavins Point to reach 7 for January 1970 flow rates is on the order of 8 days and the wave travel time about 6.5 days, the release would have to begin before the normal 3- to 5-day weather forecast period would provide reliable forecasts. Should a cold weather system be anticipated, the response would need to be based on known water discharge distributions and a risk-based estimate of cold snap severity.

Alternately, if the accumulated freezing-degree-days (AFDD) have been tracked as described earlier, a discharge deficit estimate can be made that accounts for the severity of the current winter. In this case, the user would check the current AFDD tabulated since 1 December, enter Figure 19 within that AFDD range and read the discharge deficit magnitude corresponding to the preselected level of risk. If a cold snap is anticipated that would increase the AFDD to the next range in Figure 19, then values in each range should also be considered in determining an appropriate response.

For example, if the January 1970 discharge scenario is assumed along with 180 AFDD, a 10% level of risk would correspond to a discharge deficit of 6,800 ft^3/s. However, if it is 3 January we could estimate (using Fig. 8a) that there is a 50% risk of a 5-day cold snap exceeding 80 FDD and a 10-day cold snap exceeding 140 FDD. In that case we would expect that in one out of two years we could go from 180 to 260 AFDD within the next 5 days and to as much as 320 AFFD within 10 days. Thus, the expected discharge deficit might actually decrease from 6,800 ft^3/s to 6,400 and then 5,300 as the cold snap contin-



a. At Yankton.

b. At Nebraska City.

c. At Booneville.

Figure 25. Probable cumulative freezing-degree-days.

ued. Of course, for the immediate future 3- to 5-day period, the weather forecast should be more reliable, but longer term operations must be dealt with in a statistical framework.

Using this method, if the weather forecast predicted the approach of a major cold front such that a significant discharge deficit event might be expected, plots corresponding to Figures 8 and 9 could be employed to determine probable cold snap severity and duration for the current time period for the various river reaches. The onset of a significant discharge deficit event typically involves a 3-day or longer cold snap with temperatures reaching –12°C (10°F) or below. If such an event is anticipated, then the current AFDD totals for the various reaches along the river, coupled with these estimates of near-term additional FDDs, would allow an assessment of expected discharge deficits at various levels of risk.

Note that the coldest weather does not always correspond to the greatest discharge deficit levels. Initially, as AFDDs increase the magnitude or the probable discharge deficit event also increases. However, as the total AFDD continues to increase, the magnitude of a discharge deficit event begins to decrease in response to water surface area already being covered by ice such that the potential or additional water storage begins to decrease. Further, the location where the discharge responds to a cold snap can vary through the winter. Figure 25 shows probable cumulative freezing-degree-day totals in 2-week time intervals. For example, at the 50% risk level, the 180 AFFD total used in the January 1970 example above would be reached in late December at Yankton, late January at Nebraska City, and not at all at Booneville.

Thus, depending on the pattern of an individual winter's weather, we might find that the magnitude of a discharge deficit event (at a given risk level) is greater in reach 1 early in the season, but greater in reach 4 at some later date when reach 1 is largely ice-covered and reach 4 still has significant open water areas. The AFDD totals should be monitored for several stations along the river and estimates of the potential discharge deficit calculated for each to determine the appropriate Gavins Point release response.

SUMMARY

This report has provided two basic approaches to the regulation of Gavins Point Dam releases during the winter ice season: a long-term seasonal statistic-based method and a short-term response method based on expected weather severity. Both methods are statistically based, but the second approach takes into account the severity of the weather preceding the date of analysis. Each method might be used on either a full-time basis throughout the winter or only when significant cold weather periods are anticipated.

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APPENDIX: STATISTICAL RESULTS OF AIR TEMPERATURE ANALYSIS

Mean and standard deviation of freezing-degree-days at Sioux Falls.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-.03	2.62
NOVEMBER	10.22	5.42
DECEMBER	13.26	4.35
JANUARY	23.16	3.88
FEBRUARY	19.67	4.64
MARCH	12.03	5.77
	2-DAY	
OCTOBER	-2.11	5.14
NOVEMBER	18.34	10.67
DECEMBER	35.18	9.82
JANUARY	43.98	7.64
FEBRUARY	36.17	9.70
MARCH	21.63	10.91
	3-DAY	
OCTOBER	-6.46	8.00
NOVEMBER	24.36	15.50
DECEMBER	47.85	14.37
JANUARY	61.46	11.73
FEBRUARY	50.54	14.06
MARCH	28.75	15.42
	5-DAY	
OCTOBER	-18.60	12.05
NOVEMBER	32.73	23.85
DECEMBER	69.72	23.36
JANUARY	91.80	20.64
FEBRUARY	73.03	23.27
MARCH	39.35	24.52
	10-DAY	
OCTOBER	-60.54	24.09
NOVEMBER	37.11	38.45
DECEMBER	113.92	49.34
JANUARY	155.70	42.45
FEBRUARY	119.63	45.33
MARCH	52.15	43.55

Mean and standard deviation of freezing-degree-days at Gavins Point.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-1.07	2.65
NOVEMBER	6.49	4.83
DECEMBER	17.04	5.43
JANUARY	21.97	3.93
FEBRUARY	16.37	4.91
MARCH	10.67	4.99
	2-DAY	
OCTOBER	-4.86	5.96
NOVEMBER	14.76	9.43
DECEMBER	30.86	10.85
JANUARY	40.58	7.78
FEBRUARY	33.27	9.42
MARCH	19.09	9.51
	3-DAY	
OCTOBER	-9.99	9.31
NOVEMBER	16.69	13.40
DECEMBER	41.64	16.21
JANUARY	56.95	12.31
FEBRUARY	45.76	13.80
MARCH	24.96	13.41
	5-DAY	
OCTOBER	-24.85	15.11
NOVEMBER	22.65	19.86
DECEMBER	61.23	26.70
JANUARY	65.96	22.12
FEBRUARY	66.40	23.49
MARCH	33.13	24.01
	10-DAY	
OCTOBER	-72.24	28.39
NOVEMBER	15.00	36.83
DECEMBER	96.19	51.26
JANUARY	139.91	42.56
FEBRUARY	106.79	46.39
MARCH	37.67	44.79

Mean and standard deviation of freezing-degree-days at Yankton.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-.56	2.47
NOVEMBER	9.47	5.14
DECEMBER	17.97	4.64
JANUARY	21.89	3.86
FEBRUARY	16.37	4.45
MARCH	11.43	5.55
	2-DAY	
OCTOBER	-3.69	5.19
NOVEMBER	16.50	9.61
DECEMBER	31.63	9.66
JANUARY	40.69	7.66
FEBRUARY	33.98	9.15
MARCH	20.63	10.46
	3-DAY	
OCTOBER	-6.77	6.12
NOVEMBER	21.06	14.26
DECEMBER	43.19	14.46
JANUARY	57.10	11.79
FEBRUARY	46.38	13.55
MARCH	27.37	14.76
	5-DAY	
OCTOBER	-22.94	12.90
NOVEMBER	25.53	22.14
DECEMBER	63.23	24.77
JANUARY	84.34	21.72
FEBRUARY	66.40	23.09
MARCH	37.85	24.29
	10-DAY	
OCTOBER	-66.87	22.75
NOVEMBER	25.64	36.44
DECEMBER	104.21	46.96
JANUARY	140.79	43.47
FEBRUARY	106.90	46.65
MARCH	47.98	44.92

Mean and standard deviation of freezing-degree-days at Vermillion.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-1.67	3.00
NOVEMBER	8.27	5.19
DECEMBER	16.90	5.65
JANUARY	20.66	3.63
FEBRUARY	17.74	5.10
MARCH	9.94	5.33
	2-DAY	
OCTOBER	-6.56	5.91
NOVEMBER	13.92	9.60
DECEMBER	29.34	11.11
JANUARY	38.30	7.71
FEBRUARY	30.69	9.00
MARCH	17.04	9.84
	3-DAY	
OCTOBER	-13.60	6.88
NOVEMBER	17.53	14.18
DECEMBER	39.65	16.63
JANUARY	52.97	11.17
FEBRUARY	41.94	13.66
MARCH	22.13	13.97
	5-DAY	
OCTOBER	-31.56	13.95
NOVEMBER	20.56	21.90
DECEMBER	56.75	27.26
JANUARY	78.63	21.30
FEBRUARY	57.49	23.14
MARCH	27.63	22.27
	10-DAY	
OCTOBER	-63.31	27.36
NOVEMBER	5.56	39.28
DECEMBER	91.29	53.25
JANUARY	126.56	44.35
FEBRUARY	67.07	49.37
MARCH	26.57	41.66

Mean and standard deviation of freezing-degree-days at Nebraska City.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-3.19	2.61
NOVEMBER	5.93	4.26
DECEMBER	13.46	5.50
JANUARY	17.93	3.70
FEBRUARY	14.06	4.68
MARCH	7.76	4.61
	2-DAY	
OCTOBER	-6.78	5.52
NOVEMBER	9.56	8.01
DECEMBER	23.41	10.21
JANUARY	33.35	7.66
FEBRUARY	25.65	9.42
MARCH	13.01	8.97
	3-DAY	
OCTOBER	-16.73	8.41
NOVEMBER	11.14	11.69
DECEMBER	31.34	15.42
JANUARY	45.72	11.06
FEBRUARY	33.17	13.96
MARCH	16.34	12.71
	5-DAY	
OCTOBER	-35.40	13.93
NOVEMBER	9.53	17.57
DECEMBER	43.04	25.56
JANUARY	66.09	19.71
FEBRUARY	45.04	23.99
MARCH	18.67	19.42
	10-DAY	
OCTOBER	-92.21	25.59
NOVEMBER	-5.16	29.56
DECEMBER	64.56	50.68
JANUARY	103.86	39.57
FEBRUARY	67.53	47.56
MARCH	10.25	38.23

Mean and standard deviation of freezing-degree-days at St. Joseph.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-.12	4.69
NOVEMBER	7.24	4.67
DECEMBER	15.36	6.05
JANUARY	19.55	5.72
FEBRUARY	16.61	7.75
MARCH	9.42	5.86
	2-DAY	
OCTOBER	-2.76	9.67
NOVEMBER	12.33	9.43
DECEMBER	26.10	12.07
JANUARY	36.15	11.61
FEBRUARY	29.77	14.96
MARCH	16.44	11.09
	3-DAY	
OCTOBER	-7.49	14.00
NOVEMBER	14.58	13.34
DECEMBER	36.65	16.64
JANUARY	50.06	16.45
FEBRUARY	39.64	22.23
MARCH	21.08	15.40
	5-DAY	
OCTOBER	-19.63	24.04
NOVEMBER	16.10	20.57
DECEMBER	49.86	26.65
JANUARY	72.66	26.62
FEBRUARY	55.20	36.32
MARCH	26.78	23.87
	10-DAY	
OCTOBER	-59.94	47.56
NOVEMBER	9.69	36.52
DECEMBER	75.44	51.65
JANUARY	119.00	52.95
FEBRUARY	85.78	66.84
MARCH	27.19	41.91

Mean and standard deviation of freezing-degree-days at Atchison.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-5.24	2.69
NOVEMBER	4.26	3.72
DECEMBER	12.36	5.09
JANUARY	15.44	4.06
FEBRUARY	11.13	4.73
MARCH	5.74	4.81
	2-DAY	
OCTOBER	-12.91	5.39
NOVEMBER	6.02	7.04
DECEMBER	21.54	10.26
JANUARY	27.25	8.23
FEBRUARY	19.13	9.36
MARCH	8.49	9.37
	3-DAY	
OCTOBER	-22.26	8.05
NOVEMBER	5.64	10.38
DECEMBER	27.08	15.14
JANUARY	36.30	12.17
FEBRUARY	23.67	13.73
MARCH	8.60	13.04
	5-DAY	
OCTOBER	-44.09	13.77
NOVEMBER	.59	16.42
DECEMBER	34.56	23.35
JANUARY	50.39	20.69
FEBRUARY	29.66	22.02
MARCH	5.79	21.12
	10-DAY	
OCTOBER	-112.42	22.94
NOVEMBER	-24.04	24.98
DECEMBER	44.84	44.77
JANUARY	72.66	42.71
FEBRUARY	38.08	43.61
MARCH	-15.00	40.74

Mean and standard deviation of freezing-degree-days at Kansas City.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-5.60	2.90
NOVEMBER	3.47	3.95
DECEMBER	10.67	5.54
JANUARY	14.99	4.24
FEBRUARY	10.65	5.11
MARCH	4.97	4.37
	2-DAY	
OCTOBER	-13.40	6.06
NOVEMBER	4.91	7.56
DECEMBER	18.64	10.55
JANUARY	26.63	7.66
FEBRUARY	18.72	9.98
MARCH	7.66	8.91
	3-DAY	
OCTOBER	-23.09	9.19
NOVEMBER	4.35	10.94
DECEMBER	23.64	15.01
JANUARY	36.11	11.57
FEBRUARY	23.62	14.82
MARCH	7.66	11.96
	5-DAY	
OCTOBER	-45.56	15.24
NOVEMBER	-1.73	16.78
DECEMBER	28.57	23.18
JANUARY	49.63	19.93
FEBRUARY	29.83	23.89
MARCH	4.97	18.82
	10-DAY	
OCTOBER	-111.23	27.70
NOVEMBER	-26.51	28.05
DECEMBER	34.90	44.18
JANUARY	71.91	41.07
FEBRUARY	36.53	47.45
MARCH	-17.10	35.32

Mean and standard deviation of freezing-degree-days at Lexington.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-4.96	3.04
NOVEMBER	3.91	3.52
DECEMBER	10.60	4.74
JANUARY	14.61	4.74
FEBRUARY	10.93	4.60
MARCH	4.96	4.36
	2-DAY	
OCTOBER	-11.66	6.03
NOVEMBER	5.63	6.96
DECEMBER	16.97	9.21
JANUARY	27.19	9.50
FEBRUARY	19.26	9.77
MARCH	7.63	8.84
	3-DAY	
OCTOBER	-20.01	8.76
NOVEMBER	5.45	10.32
DECEMBER	24.90	13.51
JANUARY	36.02	14.06
FEBRUARY	25.01	14.36
MARCH	7.61	13.17
	5-DAY	
OCTOBER	-40.65	14.72
NOVEMBER	1.00	15.64
DECEMBER	32.63	21.27
JANUARY	49.44	23.26
FEBRUARY	31.20	22.81
MARCH	4.38	20.54
	10-DAY	
OCTOBER	-106.19	27.63
NOVEMBER	-23.48	24.63
DECEMBER	42.05	42.46
JANUARY	71.68	44.72
FEBRUARY	37.48	43.54
MARCH	-17.20	39.58

Mean and standard deviation of freezing-degree-days at Booneville.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-4.94	2.67
NOVEMBER	4.18	3.45
DECEMBER	11.42	5.01
JANUARY	15.33	4.40
FEBRUARY	11.65	5.00
MARCH	5.46	4.49
	2-DAY	
OCTOBER	-11.71	5.27
NOVEMBER	6.33	6.85
DECEMBER	20.26	10.10
JANUARY	28.59	8.37
FEBRUARY	20.92	9.51
MARCH	9.11	9.02
	3-DAY	
OCTOBER	-20.33	7.94
NOVEMBER	6.26	10.32
DECEMBER	26.46	14.59
JANUARY	38.17	11.15
FEBRUARY	27.19	14.01
MARCH	9.73	12.97
	5-DAY	
OCTOBER	-41.41	13.43
NOVEMBER	1.20	14.71
DECEMBER	33.87	23.15
JANUARY	52.46	16.61
FEBRUARY	34.81	20.92
MARCH	7.56	19.11
	10-DAY	
OCTOBER	-104.09	25.56
NOVEMBER	-22.49	25.59
DECEMBER	44.42	46.64
JANUARY	75.56	34.58
FEBRUARY	45.02	41.96
MARCH	-6.44	35.16

Mean and standard deviation of freezing-degree-days at Jefferson.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-5.01	2.91
NOVEMBER	3.55	3.36
DECEMBER	11.17	5.14
JANUARY	13.56	4.87
FEBRUARY	9.67	4.71
MARCH	4.34	4.11
	2-DAY	
OCTOBER	-11.77	5.66
NOVEMBER	4.66	6.52
DECEMBER	16.47	9.49
JANUARY	23.68	9.26
FEBRUARY	16.92	9.47
MARCH	5.62	8.12
	3-DAY	
OCTOBER	-20.09	8.41
NOVEMBER	4.32	9.42
DECEMBER	23.27	13.70
JANUARY	31.53	13.92
FEBRUARY	21.71	13.75
MARCH	5.05	12.01
	5-DAY	
OCTOBER	-41.16	14.20
NOVEMBER	-1.17	14.12
DECEMBER	30.10	22.25
JANUARY	41.51	22.73
FEBRUARY	25.27	21.62
MARCH	.63	18.69
	10-DAY	
OCTOBER	-104.91	26.72
NOVEMBER	-27.85	24.30
DECEMBER	35.34	43.85
JANUARY	55.85	45.60
FEBRUARY	24.45	40.11
MARCH	-25.44	36.21

Mean and standard deviation of freezing-degree-days at St. Charles.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-5.32	2.77
NOVEMBER	3.13	3.33
DECEMBER	10.46	5.23
JANUARY	13.47	5.05
FEBRUARY	9.20	5.01
MARCH	3.77	4.12
	2-DAY	
OCTOBER	-12.48	5.43
NOVEMBER	3.84	6.33
DECEMBER	17.81	10.10
JANUARY	24.26	9.53
FEBRUARY	15.93	10.14
MARCH	4.76	8.47
	3-DAY	
OCTOBER	-21.56	8.15
NOVEMBER	2.93	9.28
DECEMBER	22.90	14.85
JANUARY	32.17	14.22
FEBRUARY	19.92	14.87
MARCH	3.60	12.41
	5-DAY	
OCTOBER	-43.55	12.85
NOVEMBER	-3.37	13.56
DECEMBER	30.04	24.69
JANUARY	42.59	23.61
FEBRUARY	24.24	23.36
MARCH	-2.45	19.61
	10-DAY	
OCTOBER	-109.61	26.01
NOVEMBER	-32.56	23.85
DECEMBER	38.14	50.35
JANUARY	58.16	49.87
FEBRUARY	23.20	45.05
MARCH	-29.60	39.78

Mean and standard deviation of freezing-degree-days at St. Louis W.

MONTH	MEAN (°C-day)	ST DEV (°C-day)
	1-DAY	
OCTOBER	-5.85	2.47
NOVEMBER	3.27	3.92
DECEMBER	9.69	5.06
JANUARY	14.04	4.32
FEBRUARY	10.04	4.82
MARCH	4.00	4.35
	2-DAY	
OCTOBER	-13.26	5.09
NOVEMBER	4.21	6.83
DECEMBER	16.56	9.50
JANUARY	24.82	7.77
FEBRUARY	17.41	8.73
MARCH	5.87	8.25
	3-DAY	
OCTOBER	-22.56	7.69
NOVEMBER	2.70	9.67
DECEMBER	20.89	13.49
JANUARY	33.20	11.38
FEBRUARY	21.60	12.47
MARCH	5.80	12.15
	5-DAY	
OCTOBER	-44.12	12.08
NOVEMBER	-3.89	14.20
DECEMBER	25.24	20.56
JANUARY	44.44	17.49
FEBRUARY	26.51	18.99
MARCH	.88	17.99
	10-DAY	
OCTOBER	-109.65	23.52
NOVEMBER	-32.23	23.08
DECEMBER	27.16	39.65
JANUARY	62.38	37.04
FEBRUARY	28.65	37.90
MARCH	-23.23	36.34

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In recent years, drought conditions in the Missouri River basin have required more accurate control of releases at Gavins Point Dam, the furthermost downstream flow control structure on the river, to meet competing water needs for irrigation and recreation upstream and for navigation and municipal and industrial water supply downstream. In winter, ice accumulations can seriously affect flow distribution along the river. This paper summarizes a study of such ice effects. It proposes methods to determine minimum flow releases at Gavins Point Dam to meet downstream water supply without unduly depleting upstream reservoirs.

14. SUBJECT TERMS

Drought	Ice	Ice hydraulics	Reservoir regulation
Flow regulation	Ice cover	Ice jams	River ice

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